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LEVEL II

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LIGHTNING TRANSIENT RESEARCH ON AN F-111E AIRCRAFT

TECHNOLOGY/SCIENTIFIC SERVICES, INC.
AIR FORCE FLIGHT DYNAMICS LABORATORY (AFFDL)
ELECTROMAGNETIC HAZARDS GROUP (FES)

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This technical report has been reviewed and is approved for publication.

Vernon L. Mangold
Project Engineer

FOR THE COMMANDER

AMBROSE B. NUTT, Director
Vehicle Equipment Division

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A simulated lightning test was conducted on an F-111E aircraft (S/N 67-116A) to field test improved measurement techniques and to record and evaluate induced transient voltages on selected electrical circuits to determine their susceptibility to lightning. Technical improvements included (1) a pneumatic system to trigger the simulated lightning current-producing capacitor bank, (2) a change in configuration of current return leads, (3) specially designed breakout boxes and cables, (4) a fiber optics measurement

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cont. system, and (5) a Tektronix transient digitizer data recording system.

The standard 2 x 50 microsecond current pulse was applied to the aircraft (nose-to-tail) and induced voltages were measured and recorded both in the time and frequency domains on 17 different circuits with power off in the aircraft. The magnitude of the current pulse was varied from 0.5 to 5.5 kiloamperes, but most measurements were made at 2.5 kiloamperes. Measurements were made on flight critical circuits of the Altitude-Vertical Speed amplifiers, the Yaw and Roll computers, and the Roll Rate Gyro in the Feel and Trim assembly, on the tail light and right and left wing position light circuits, on the fuel indication circuits, and on the pitot heater circuit (with and without a transient suppressor device). Power-on measurements made on four damper servo circuits resulted in substantially higher induced voltage amplitudes than with power off. Changing aircraft ground points did not affect the magnitude or waveshape of induced transients.

The tail light circuit exhibited linear induced voltage response for input current of 1.8 to 5.5 kiloamperes; however, the Yaw Damper servo circuit produced essentially a constant induced voltage response over a range of input currents of 0.5 to 3.4 kiloamperes.

Induced voltages were highest in the pitot heater circuit and the fuel indicator circuits. Dominant frequencies in the various circuits ranged from 2 MHz to 20.5 MHz.

LEVEL II

FOREWORD

This report was prepared by the Survivability/Vulnerability Branch, Vehicle Equipment Division, Air Force Flight Dynamics Laboratory. This work was initiated under Project No. 4363, Task No. 436301. The data documented in this report was collected during June of 1976 at Eglin Air Force Base, Florida, with Mr. Vernon L. Mangold (FES) as project engineer.

On-site contractor support was provided by Technology/Scientific Services, Incorporated under contract F33601-75-C-0120. Mr. Lawrence C. Walko was senior engineer, John G. Schneider was test engineer and William O. Adams was lead technician.

TABLE OF CONTENTS

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TABLE OF CONTENTS (CONT'D)

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I
OBJECTIVES

The multiple objectives of this research program are to:

1.1 Increase confidence in the lightning test technique by improvement of the basic measurement techniques and data gathering systems.

1.2 Increase confidence by correlating transient test results to the inflight damage history of the F-111, as contained in AFISC lightning strike incident reports.

1.3 Evaluate the susceptibility of selected circuits of the F-111E flight control system and other systems to the severe (200 kiloampere peak magnitude, 100 kiloampere/microsecond rate-of-rise) lightning strike threat.

SECTION II
SUMMARY

The test program on the F-111E was done to improve the technique for obtaining information on the effect of lightning strikes to aircraft. To that end, a number of technical advancements were made. These improvements are listed below.

2.1 A pneumatic system was designed and used to trigger the simulated lightning current-producing capacitor bank. This system takes the place of an electronic system.

The pneumatic triggering system eliminates extraneous electrical noise caused by an electronic triggering system. The simplicity of the design of the pneumatic system insures a more reliable trigger. The electrical isolating properties of a pneumatic system eliminate ground current loops within the test setup, increasing the accuracy of measurements and also increasing personnel safety.

2.2 The change in configuration of the current return leads, using a symmetrical multi-wire design, decreased the overall inductance of the test circuit and reduced the possibility that the return currents could influence measurements on circuits made inside the aircraft.

2.3 The design and fabrication of break-out boxes and cables specifically for lightning transient research is a major improvement on the test equipment to actual aircraft circuitry.

The cables add a minimum of length to the circuit under test, thus altering the characteristics of the circuit as little as possible. The design of the break-out box permits one to monitor all circuits in a multi-conductor cable bundle simply by changing connections within the break-out box. To reduce extraneous noise pickup, the break-out box and cables were built using standard shielding practices using a solid steel box with RF gaskets around openings and copper braid placed over the cables.

2.4 The design, fabrication and use of a fiber optics system to relay electrical transient levels from the point of measurement to recording equipment demonstrated that such a system is compatible with the basic lightning transient test technique. The fiber optics system is capable of obtaining transient information without the influence of extraneous electrical noise and with no loss in signal due to the impedances of coaxial and triaxial cables formerly used for such measurements.

The fiber optics system as it exists today is a useful step in the design and future development of a multiplex system for simultaneous measurement of lightning transients on aircraft circuits.

2.5 The use of a Tektronix transient digitizer data recording system increased the efficiency of data gathering. Whereas all data from former lightning investigations has been recorded on Polaroid film,

it was now possible to record all data on magnetic tape in digital format to be replayed and analyzed, permitting such processing as Fast Fourier Transform of oscillatory transients to obtain dominant frequencies of the transients.

By using the equipment and systems described above, it was possible to obtain lightning transient data on F-111E circuits that could be useful in determining the effect of lightning on F-111E electrical circuitry. The following activities were carried out to obtain such information.

1. Lightning induced voltages were measured on flight critical circuits of the Altitude-Vertical Speed amplifiers, the Yaw and Roll computers, and the Roll Rate Gyro circuit in the Feel and Trim assembly. A number of measurements were made on each circuit to improve the accuracy of the measurements. Frequency information was obtained by calculating the Fast Fourier Transform of the transient using the Tektronix digitizer system.

2. A program was carried out to determine the degree of protection afforded by a transient suppressor, developed by General Electric, on the Pitot Heater circuit of the F-111E aircraft. From the tests performed, the suppressor seemed to approach its stated design capabilities. Testing at higher applied current levels could yield additional information.

3. Transient measurements were made on the damper servo circuits with power on the aircraft. From the data obtained, transients on these circuits tended to be of higher value than with power off. Since power-on measurements were made only on the servo circuits, there is inconclusive evidence that all circuits would react this way with power on. However, there is some evidence from previous tests that there is a trend toward higher transient levels with power on.

4. By varying the point where the F-111E aircraft was grounded during the tests, it was determined from the transient levels measured that changing the ground point does not affect the magnitude or waveshape of the transient measured. Since a transient on a circuit is directly related to the applied current and its flow path, it was verified that current does not flow from the aircraft to the ground point, but does indeed flow along the aircraft and return to the lightning-forming capacitor bank.

5. From an exercise in pulsing the servo circuits with a square wave voltage, the subsequent reflections observed on the circuits suggest that a lightning transient is influenced by the mismatched load impedance and surge impedance of the circuits.

6. By varying the magnitude of the input current to the airplane, it was possible to obtain various transient levels on the Tail Light circuit to investigate the linear extrapolation

concept. For a simple circuit, such as the Tail Light circuit, linearity holds. The increase in the number of measurements made at each current level improves the degree of linearity observed on the circuit.

SECTION III
LIGHTNING SIMULATION

The apparatus used to generate a current impulse similar in shape to the unidirectional fast rising current wave of a lightning strike has been described in previous reports (Ref. 1).

3.1 Lightning Current Generator

The lightning current generator used for the tests on the F-111E aircraft is the latest development of this type of apparatus (Figures 1 and 2). Using two separate banks of parallel capacitors, each bank is charged separately. When the desired voltage is reached, the banks are discharged in series through the use of a pneumatically propelled sphere. The use of pneumatics instead of an electronic device to trigger the generator greatly simplifies the procedure since the gap spacing does not have to be critical for voltage breakdown; the movable sphere reduces the gap spacing for breakdown. Also, the random electrical noise associated with an electronically triggered gap is eliminated, increasing the validity of the transient measurement.

When the main gap is triggered, the full potential of the charged capacitor banks causes the other two gaps to break down. The current output of the generator flows through the circuit, which in this

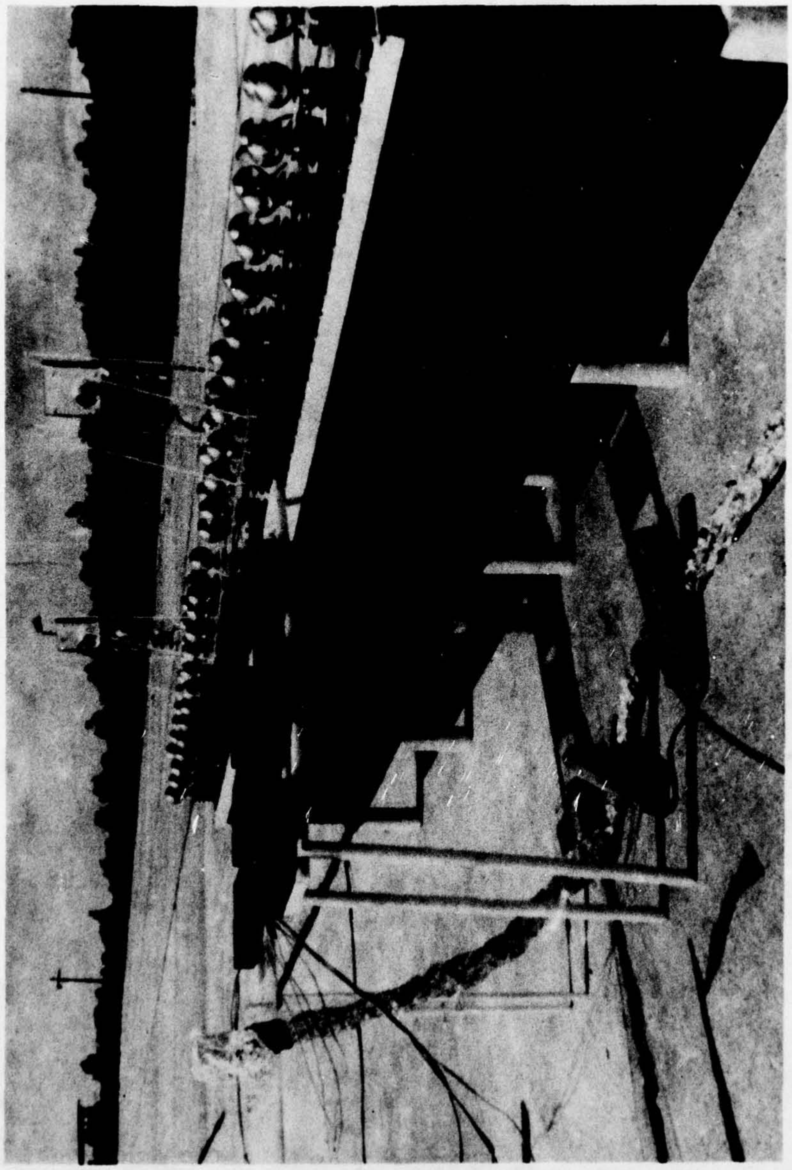


FIGURE 1
TWO-STAGE MARX-TYPE CURRENT
IMPULSE GENERATOR

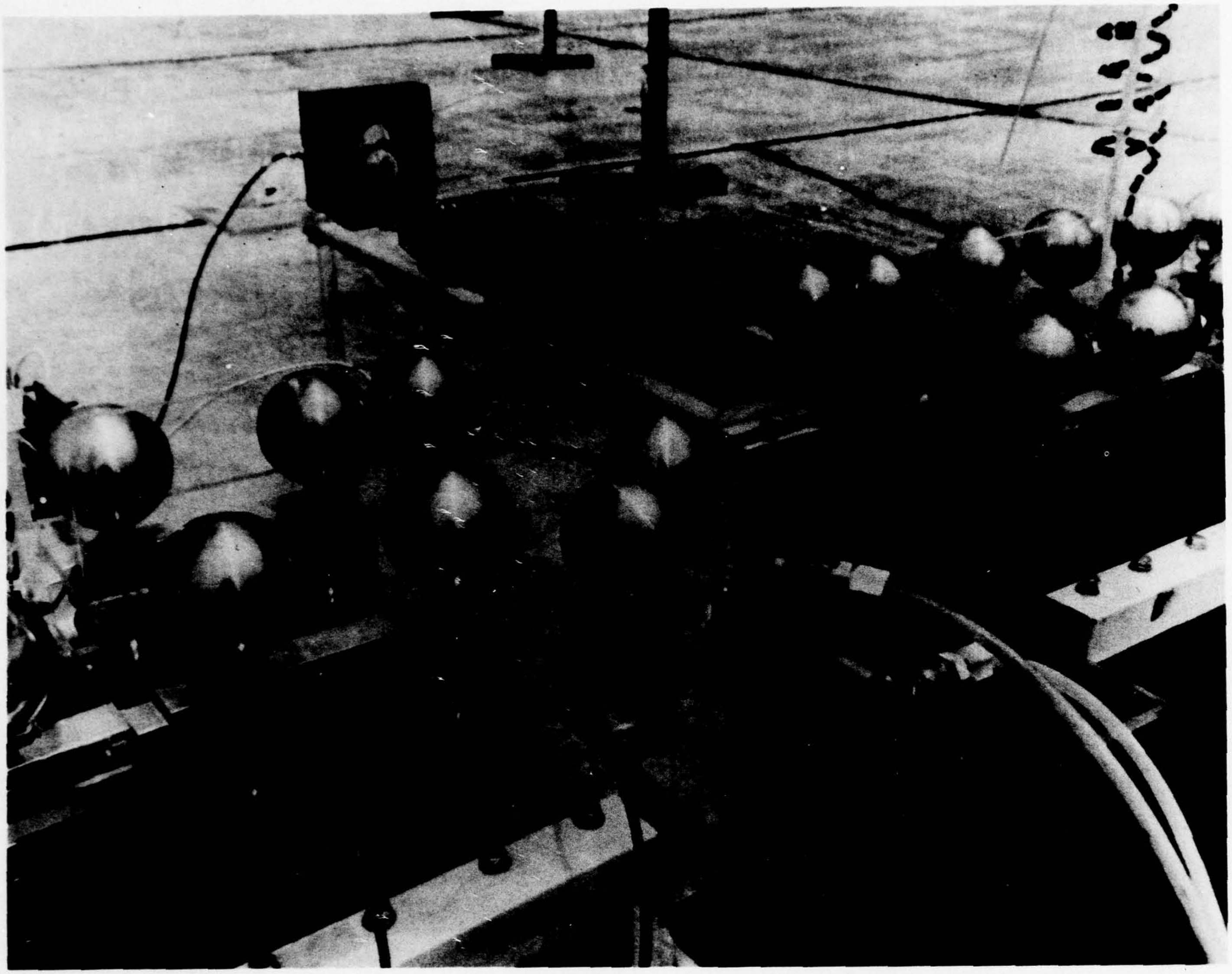


FIGURE 2

DETAIL OF MARX-TYPE
CURRENT IMPULSE GENERATOR

case are the aircraft and return leads.

The applied current waveshape had a risetime of a few microseconds and a decay time of approximately 50 microseconds.

In addition to the generator being pneumatically triggered, the capacitor banks are grounded and shorted by pneumatic devices using the same pneumatic system (Figure 3). The system utilizes an air compressor or can be operated with compressed gas such as nitrogen.

3.2 Circuit Configuration and Current Return Path

One of the basic concepts of the test technique used for lightning transients research on the F-111E aircraft is the current flow path from the current pulse generator, through the aircraft, and back to the current generator. Figure 4 shows the circuit used on the F-111E. The technique of injecting the current into the aircraft has changed little from earlier tests (ref. 1). One significant improvement is that lead attachment is now done by utilizing one or more of the panel screws to obtain a hard wire attachment. This has become important with the increase in applied current magnitudes. Spark-over at point of attachment can be a problem by creating extraneous electrical noise that could hamper the taking of valid measurements. The current exit point is also firmly attached at an existing screw location, usually near the tail of the aircraft.

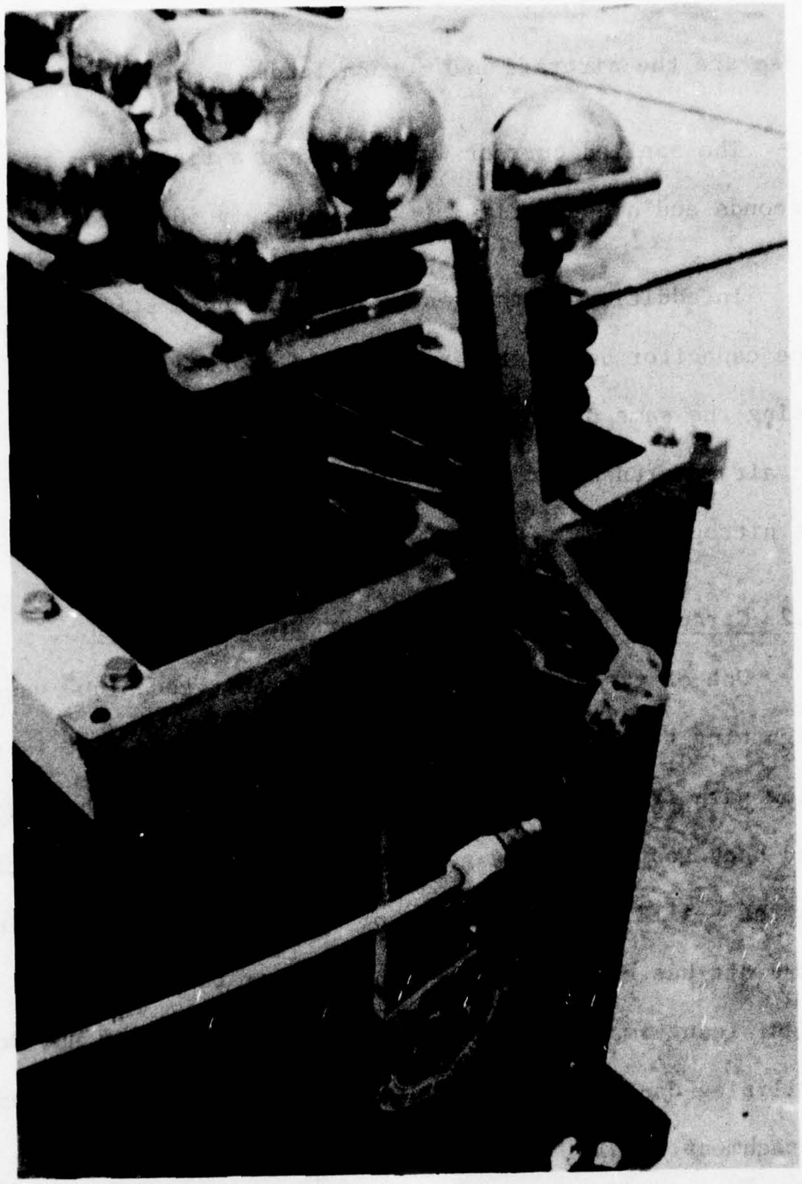


FIGURE 3

DETAIL OF PNEUMATICALLY
OPERATED SHORTING DEVICE

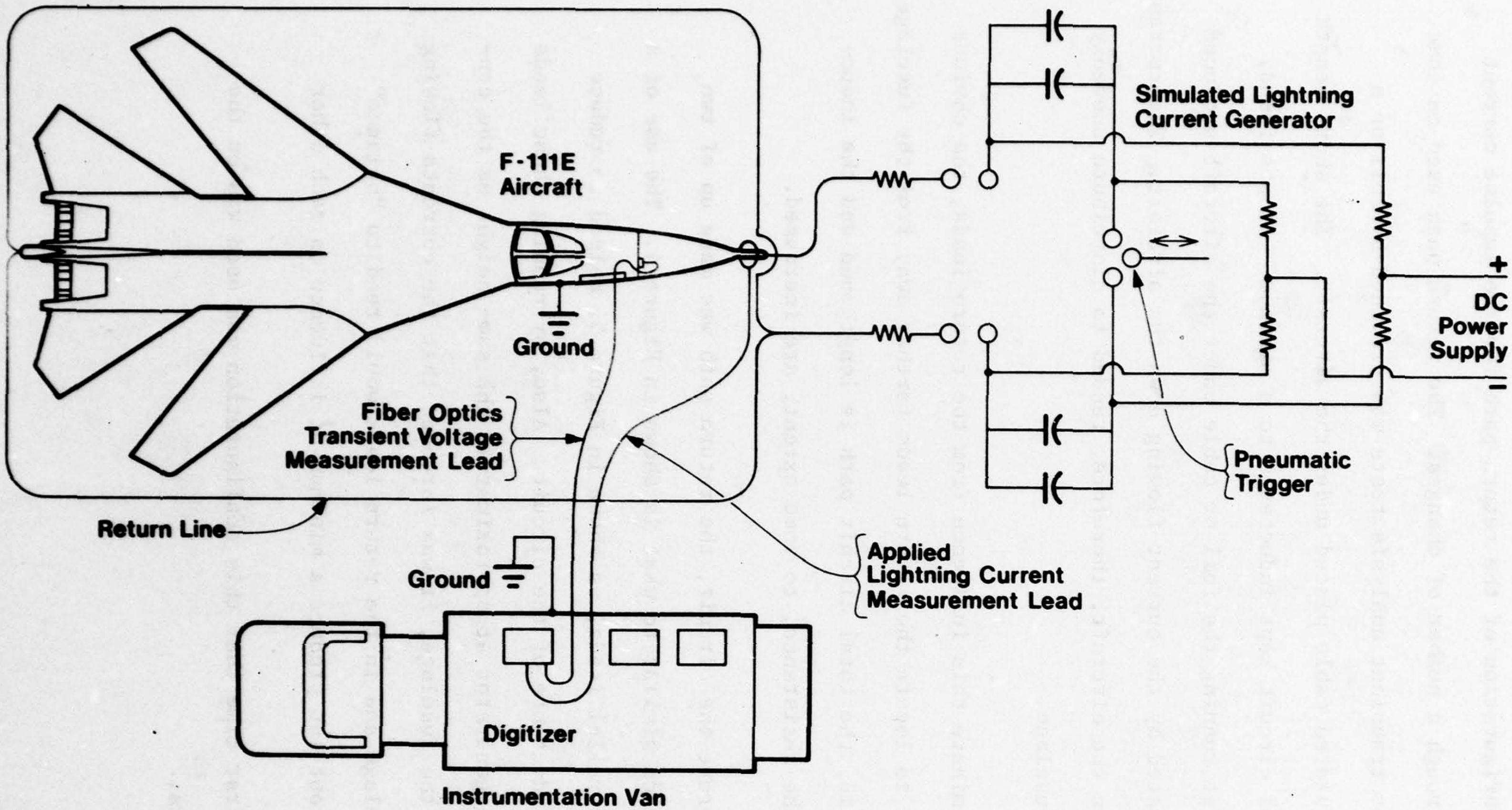


FIGURE 4

PLAN VIEW OF TEST SET-UP

The configuration of the return path for the impulse current has gone through a number of changes. The return path used on some of the first transient analysis tests was provided by foil or a 0000AWG insulated cable placed under the aircraft. The short length of the total circuit kept inductance to a minimum. It was found, however, that running the foil or cable under the aircraft produced a field created by the current flowing down the aircraft. The current flowing down the aircraft, therefore, tended to distribute unevenly along the fuselage.

To eliminate this influence from the return leads, the obvious solution is to locate the return leads farther away from the fuselage. In doing this, the total circuit path is lengthened and the inductance and the resistance, to some extent, are increased.

To improve the circuit, the return path was made up of two parallel leads similar to what is shown in Figure 4. The use of a number of parallel leads, as shown in Figure 5, helped to reduce the total inductance of the circuit. Also, by running these leads back to the generator at approximately the same height as the centerline of the fuselage, it was intended that the currents flowing in the fuselage and in the return leads would tend to "balance" themselves out and produce a minimum of influence on each other.

The first time that this configuration was used was on the F-111E tests.

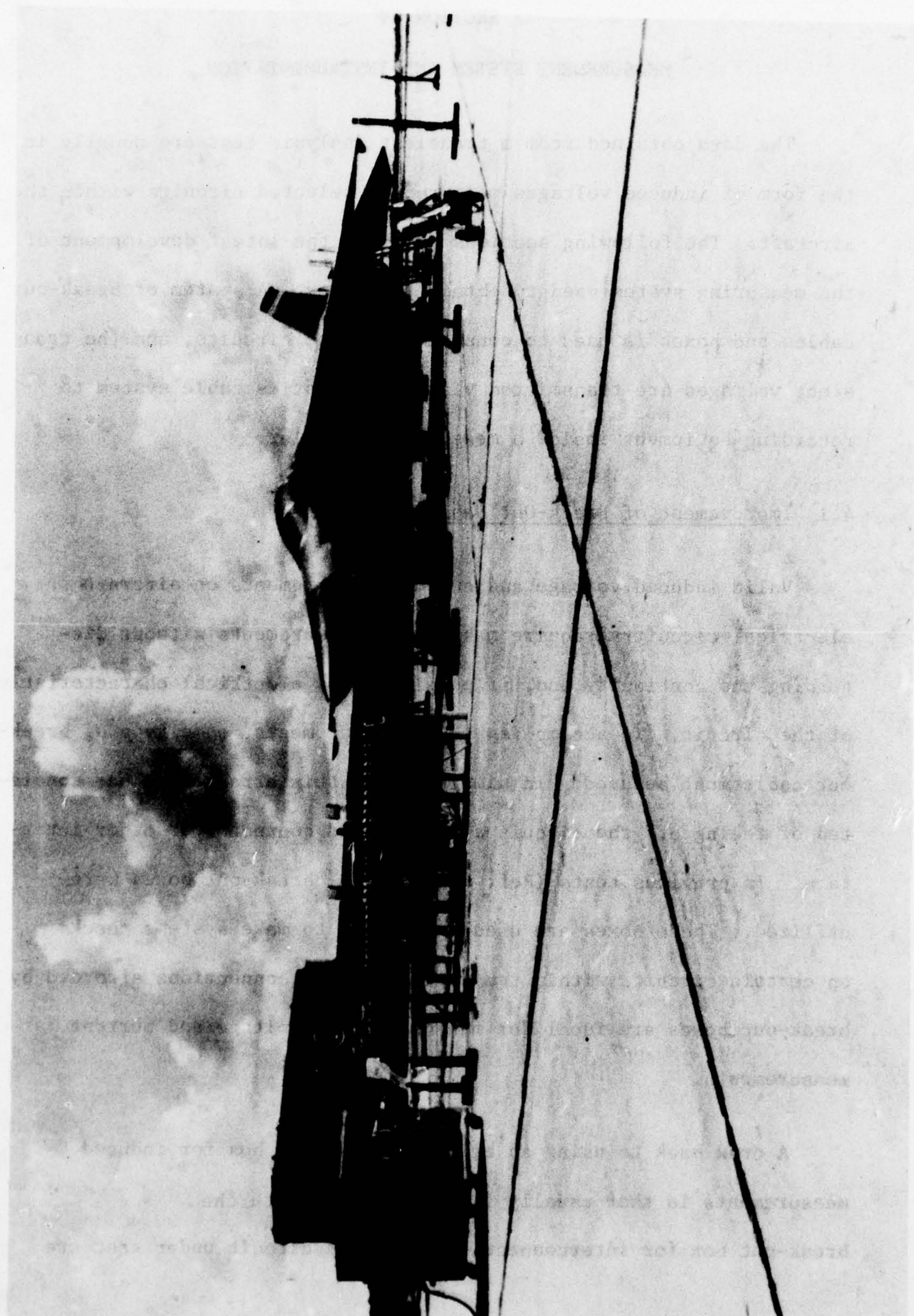


FIGURE 5
F-111E AIRCRAFT AND LIGHTNING

SECTION IV

MEASUREMENT SYSTEM AND INSTRUMENTATION

The data obtained from a transient analysis test are usually in the form of induced voltages measured on selected circuits within the aircraft. The following sections describe the latest development of the measuring system used to obtain this data. A system of break-out cables and boxes is used to connect on to the circuits, and the transient voltages are transmitted via a fiber optics cable system to recording equipment inside a measurement trailer.

4.1 Improvement of Break-Out Cable System

Valid induced voltage and current measurements on aircraft electrical circuitry require making the measurements without disturbing the continuity and, if possible, the electrical characteristics of the circuit. To accomplish these measurements, some type of break-out cable must be used. In simple terms, this arrangement has consisted of teeing off the circuit at a bulkhead connector or other interface. In previous tests (Ref. 2, 3 and 4), break-out boxes were utilized. These boxes are used originally to make systems checks on certain circuits within the aircraft. The connections afforded by break-out boxes are ideal for making induced voltage and current measurements.

A draw back to using an existing break-out box for induced measurements is that usually the cables used with the break-out box for interconnections with the circuit under test are

of such lengths as to add significantly to the overall length of the circuit. Cable lengths of up to 6 feet have been used. It has been found that circuit length is critical to the magnitude and waveshape of the transients induced on the circuit (Ref. 4). Also, the break-out box cables are usually non-shielded wire bundles conducive to noise and field pick-up. Therefore, it is possible that the induced measurements gained through the use of break-out boxes could be less valid than originally assumed.

To reduce the measurement inaccuracies produced by the use of existing break-out boxes and associated cables, a system was designed and built to be used on lightning induced transient investigations on contemporary aircraft. Figure 6 shows the major details of the break-out box system designed and built by the EM Hazards Group of AFFDL for use in making transient measurements on the F-111E aircraft.

The break-out cables used are multi-conductor bundles consisting of #20 AWG insulated wire with a braided copper shield. Figure 7 shows a representative set of cables. One end of each cable is terminated with the appropriate male or female mil-spec connector depending on the circuit tested. A number of these cables were built to cover the range of connectors used in the F-111E, from five-conductor connectors to 60-conductor connectors.

Since aircraft connectors are installed in matched pairs, the break-out cable connector had to be machined to eliminate the keys

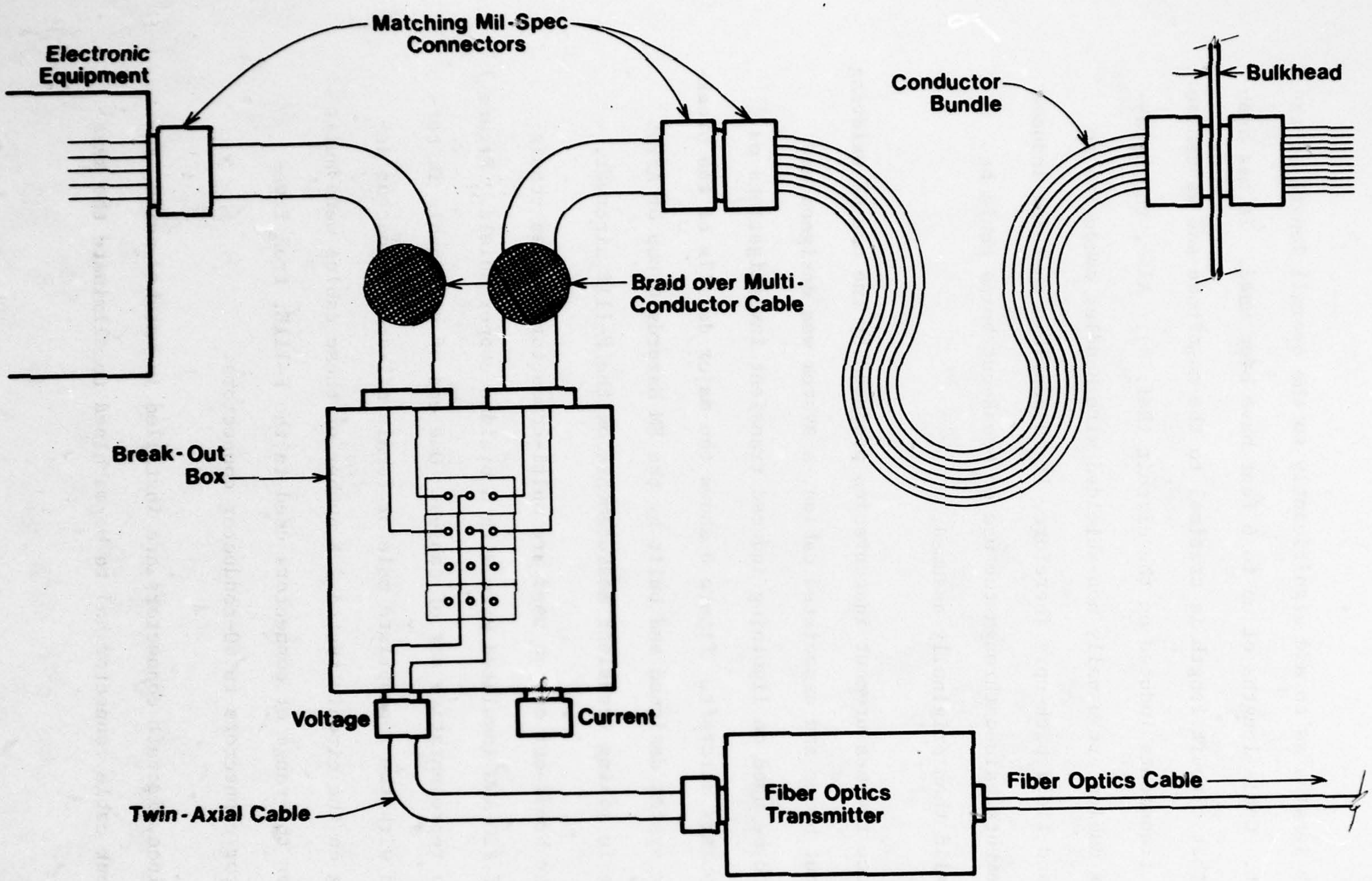


FIGURE 6

DETAIL OF BREAK-OUT BOX
USED FOR
INDUCED TRANSIENT MEASUREMENTS

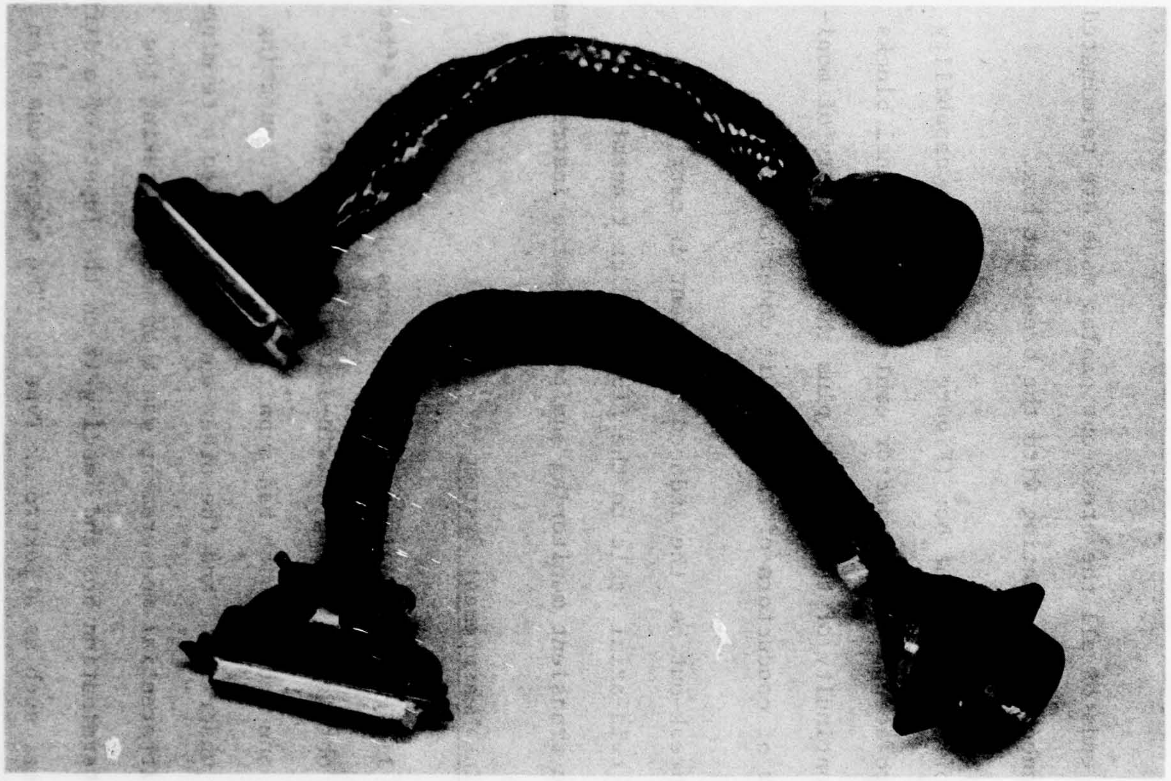


FIGURE 7

MULTICONDUCTOR CABLES USED
WITH BREAK-OUT BOX

and slots used to mate a matching set of connectors. This provided a set of connectors that would mate with any connector of that specific design.

The other ends of all the break-out cables made are terminated with Cannon connectors for mating with the break-out box.

A detail of the break-out box (Figure 8) shows the capability of the system to accept a 60-conductor cable. The terminal blocks used provide continuity of the circuit plus the capability of monitoring any pair of conductors of the circuit under test.

From the break-out box the induced transient is carried by RG-22 shielded twin-axial cable to the fiber optics transmitter and thus to the transient monitoring equipment in the instrument van.

4.2 Fiber Optics Measurement System

In former lightning transient investigations the induced effects measurements were obtained by using a twin-axial shielded cable, usually RG-22, one end of which had a pair of leads for connecting to the circuit under test, and the other end was fed into a termination box. A differential measurement was then made by taking the output of the termination box and feeding it to the inputs of a differential amplifier, such as a Tektronix Type G. The signal was then displayed on an oscilloscope screen.

It was possible to minimize the extraneous noise on the measurement circuit by taking great care to provide extra shielding for the cable and measurement hook-ups. Also, the input stages of the

FIGURE 8
INTERIOR OF BREAK-OUT BOX
SHOWING TERMINAL BLOCKS

differential amplifier had to be balanced to insure valid measurements.

A characteristic of the twin-axial cable system described above is that a hard wire connection is made to the aircraft through the circuitry measured. Also, to minimize noise, standard practice has been to place a run of aluminum foil under the twin axial measurement lead from the point of measurement to the measurement equipment, or at least to the measurement van. It has been shown that the amount of current flowing down this foil is minimal in comparison to the current flowing down the aircraft fuselage due to an impulse from the simulated lightning current generator (Ref. 1). However, the fact remains that a direct connection does exist between the aircraft under test and the measurement equipment in this test configuration, and spurious noise pickup is a problem that must always be considered.

To eliminate the need for hard wire connections to aircraft circuits and to eliminate any ground loops that might exist with aluminum foil and variable spaced grounds on the measurement equipment, a fiber optics measuring system was designed and built. Figure 9 shows a basic block diagram of the system.

The fiber optics measurement system was built to be readily adaptable to the break-out box where connections to circuits are made. Maximum input to the fiber optics transmitter is 500 millivolts either positive or negative. Coupled with a variable attenuator of up to 50:1, it is possible to accurately observe a voltage

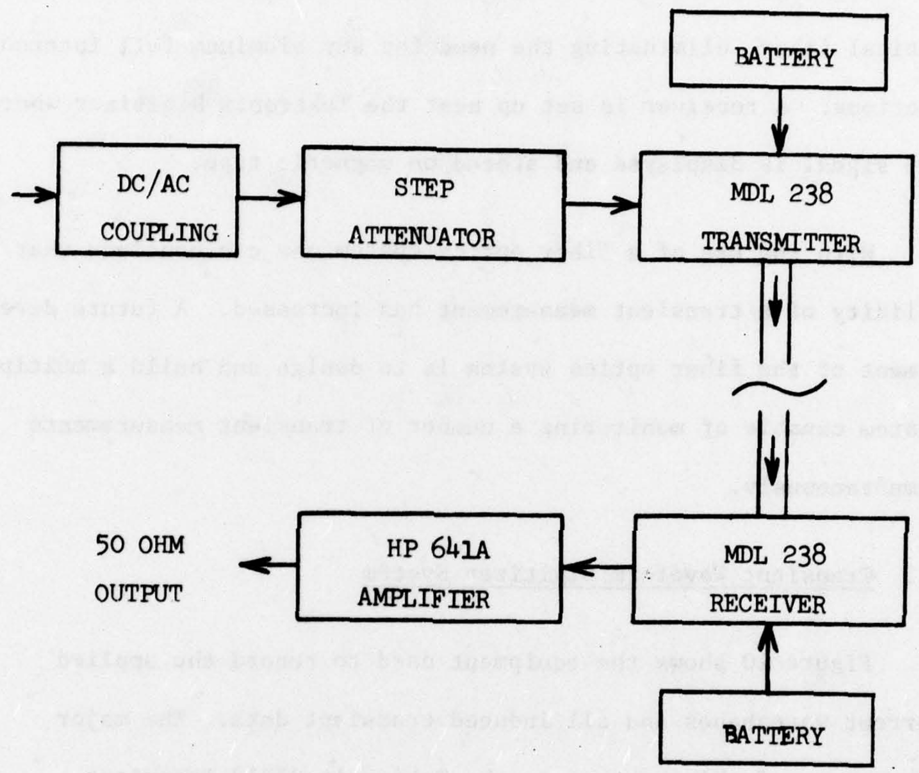


FIGURE 9
FIBER OPTICS MEASUREMENT SYSTEM

transient of up to 50 volts. The frequency response of the system has been calibrated from 2 KHz to 22 MHz.

The signal is sent through twenty meters of non-conductive optical fiber, eliminating the need for any aluminum foil interconnections. A receiver is set up near the Tektronix Digitizer where the signal is displayed and stored on magnetic tape.

With the use of a fiber optics system one can conclude that the validity of a transient measurement has increased. A future development of the fiber optics system is to design and build a multiplex system capable of monitoring a number of transient measurements simultaneously.

4.3 Transient Waveform Digitizer System

Figure 10 shows the equipment used to record the applied current waveshapes and all induced transient data. The major components of this system are the Tektronix R7912 Transient Digitizer, PDP-11/05 minicomputer, magnetic tape drive, graphics terminal and hard copy printer.

The R7912 Transient Digitizer is a high speed analog-to-digital converter that is operated like an oscilloscope, with its output either viewed on a TV monitor or fed into the minicomputer. Coupled with a 7A19 Vertical Amplifier plug-in and 7B92A Horizontal Time Base, the digitizer has an an upper bandwidth of 500 MHz.

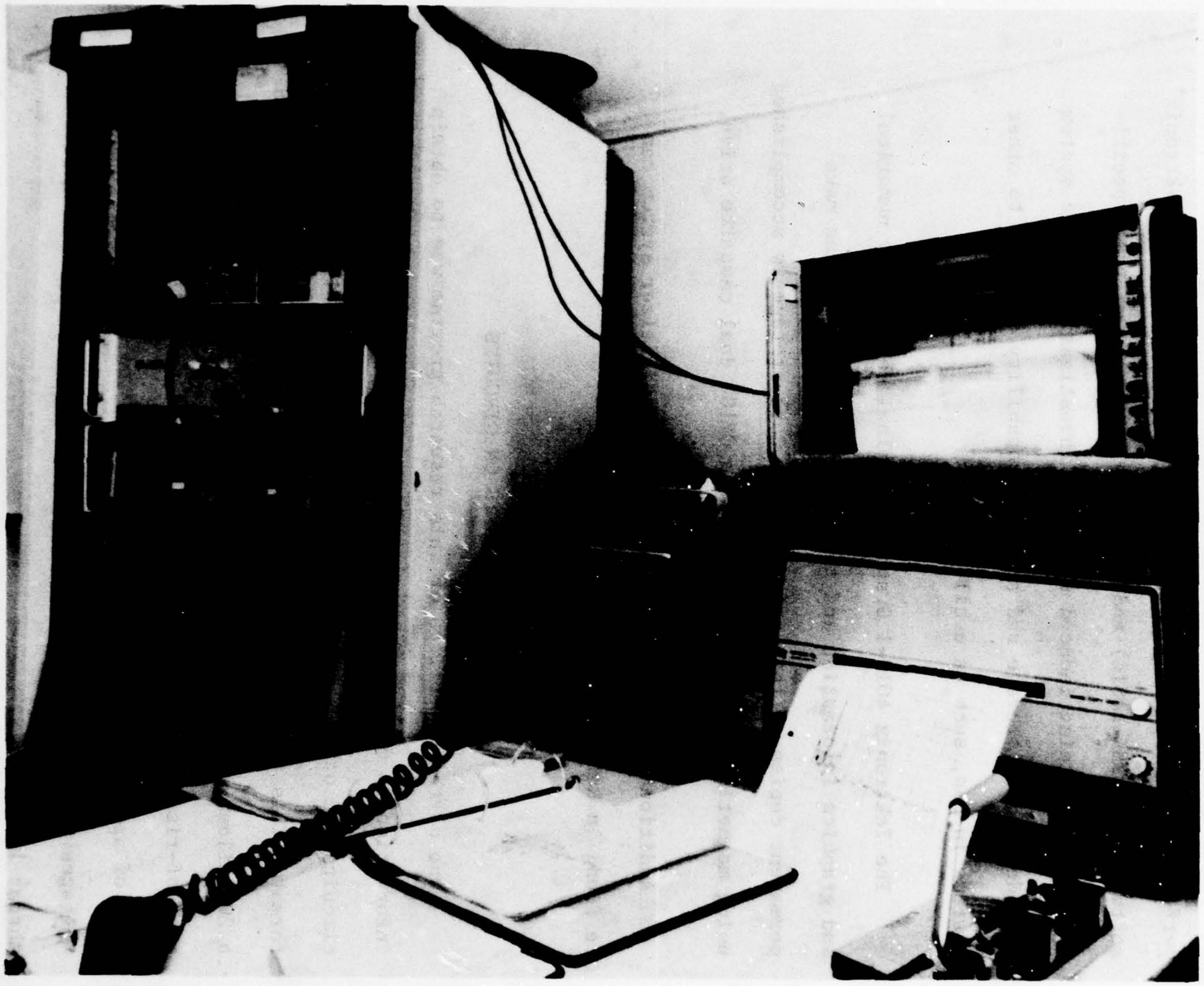


FIGURE 10

EQUIPMENT USED TO MONITOR AND RECORD SIMULATED LIGHTNING CURRENTS AND TRANSIENT VOLTAGES

The PDP-11/05 computer controls the Transient Digitizer or performs normal computations using BASIC language. With Tektronix software (WDI TEK BASIC) and additional programs written specifically for lightning induced transient investigations, this system provides a data storage and analysis capability superior to other systems in use, such as oscilloscopes.

The Tektronix 4010-1 Graphics Terminal can display numerical and graphics information and the 4610 Hard Copy Unit can make permanent copies of this information. Data storage is accomplished using magnetic tape cassettes with the CP100 dual cassette drive.

Additional information describing the digitizer system can be found in Reference 5.

SECTION V

INDUCED TRANSIENTS ON CIRCUITS

One of the objectives of this research program was to obtain information to evaluate the susceptibility of F-111E flight control circuits and other system circuits to a severe lightning strike threat. This threat is usually described as a current impulse with a 200 kiloampere peak magnitude and a 100 kiloampere-per-microsecond rate-of-rise. The current impulses applied to the F-111E aircraft were of approximately 2 kiloamperes peak. The subsequent induced voltages were extrapolated up to what they would be for the full threat level.

In keeping with the objectives of the program some of the circuits tested are linked with electronic equipment that has a history of being affected when F-111E aircraft in flight have been struck by lightning. The majority of the circuits tested are flight critical circuits. Other circuits have been chosen because of their length and location in the aircraft. The navigation light circuits are not directly associated with electronic equipment, but the length and location of these circuits suggest the possibility of substantial transient voltages being impressed on them.

5.1 Altitude-Vertical Speed Circuits

Table I lists the circuits tested. Circuits 1, 2 and 3 are in the Altitude-Vertical Speed Amplifier (AVSA). The circuits run from the AVSA to the Altitude-Vertical Velocity Indicator (AVVI). The AVSA and the AVVI have sustained damage due to lightning strikes to F-111E aircraft. The AVVI provides remote reading presentations of altitude and vertical velocity on vertical moving scales. The indicator also presents digital readout of barometric pressure and command altitude. Signals for operation of the moving scales, markers and readouts are provided from the Central Air Data Computer (CADC). Figure 11 is a schematic diagram of these circuits. The length of these circuits is approximately 5 meters; that is from the AVSA within the equipment bay covered by access door 1101 up to the AVVI in the cockpit. Figures 12, 13 and 14 display typical waveshapes of the induced voltage measured on circuits 1, 2 and 3.

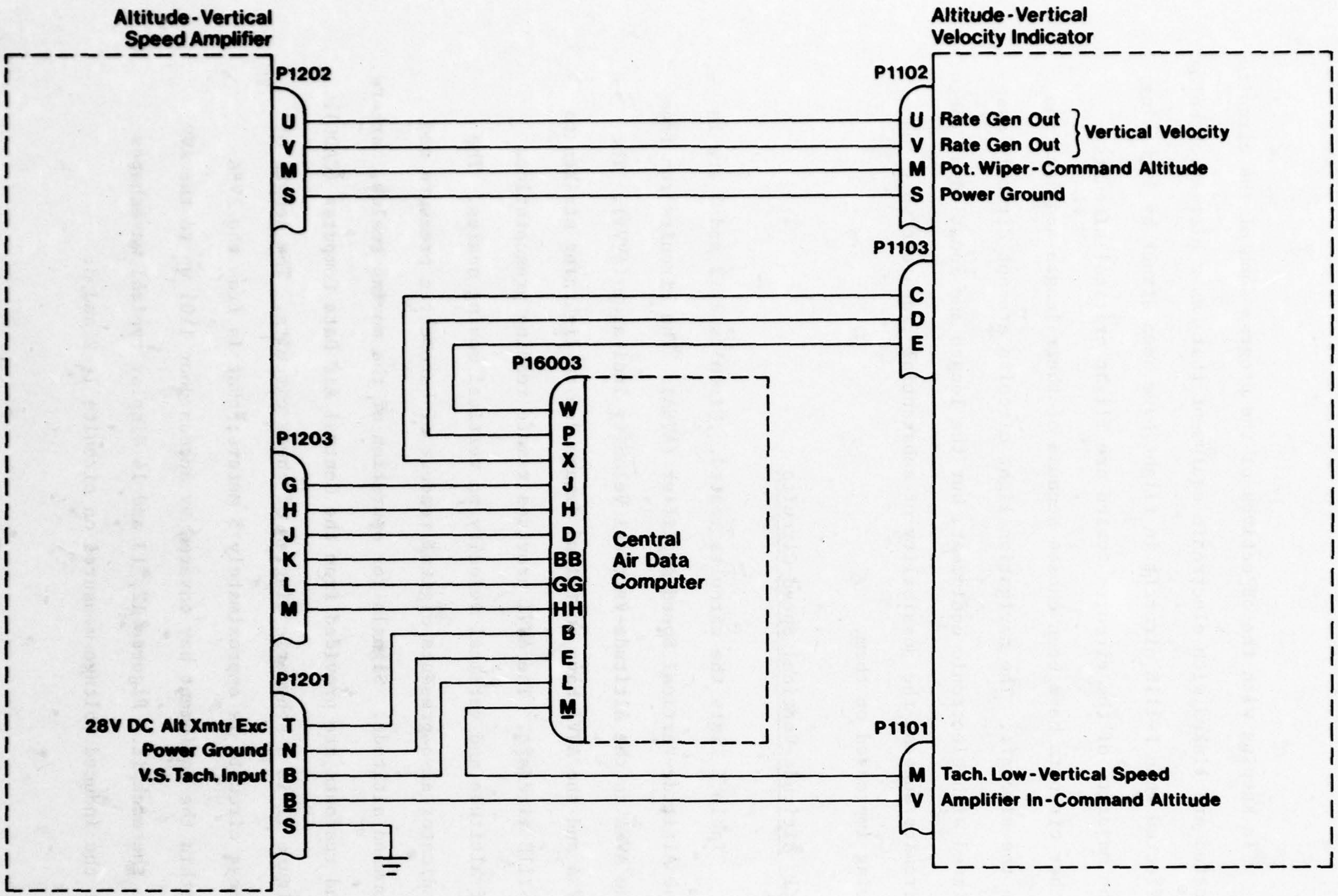


FIGURE 11

ALTITUDE-VERTICAL SPEED SCHEMATIC DIAGRAM

TABLE I

Circuits Tested on F-111E

Circuit No.	
1	Altitude - Vertical Speed Amplifier (AVSA) P1202 Pins U-V (circuit goes to AVVI) Rate Gen Out
2	AVSA P1202, Pins M-S Pot. Wiper
3	AVSA P1201, Pins B-S, Amplifier In, Command Alt
4	Yaw Computer to Yaw Damper Servo (Branch A) Pins G-H on Test Receptacle in Instrument Rack
5	Yaw Computer to Yaw Damper Servo (Branch B) Pins J-E
6	Roll Computer to Roll Damper Servo (Branch B) Pins J-E
7	Yaw Damper Servo Branch A Pins 1-3, J17041
8	Yaw Damper Servo Branch B Pins 1-3, J17042
9	Roll Damper Servo Branch A Pins 1-3, J17041
10	Roll Damper Servo Branch B Pins 1-3, J17042
11	Roll Computer to Roll Damper Servo (Branch A) Pins H-D
12	Tail Light Circuit Pins GG-P
13	RWT Nav Light Pins N-P Measured at Bulkhead
14	LWT Nav Light Pins X-P
15	Stationary Pylon Disconnect Pins 35-14 (Fuel Indication)
16	Roll Rate Gyro Measured at P200, U-AA Feel & Trim Assy
17	Pitot Heater at Radome Disconnect P1 A-B

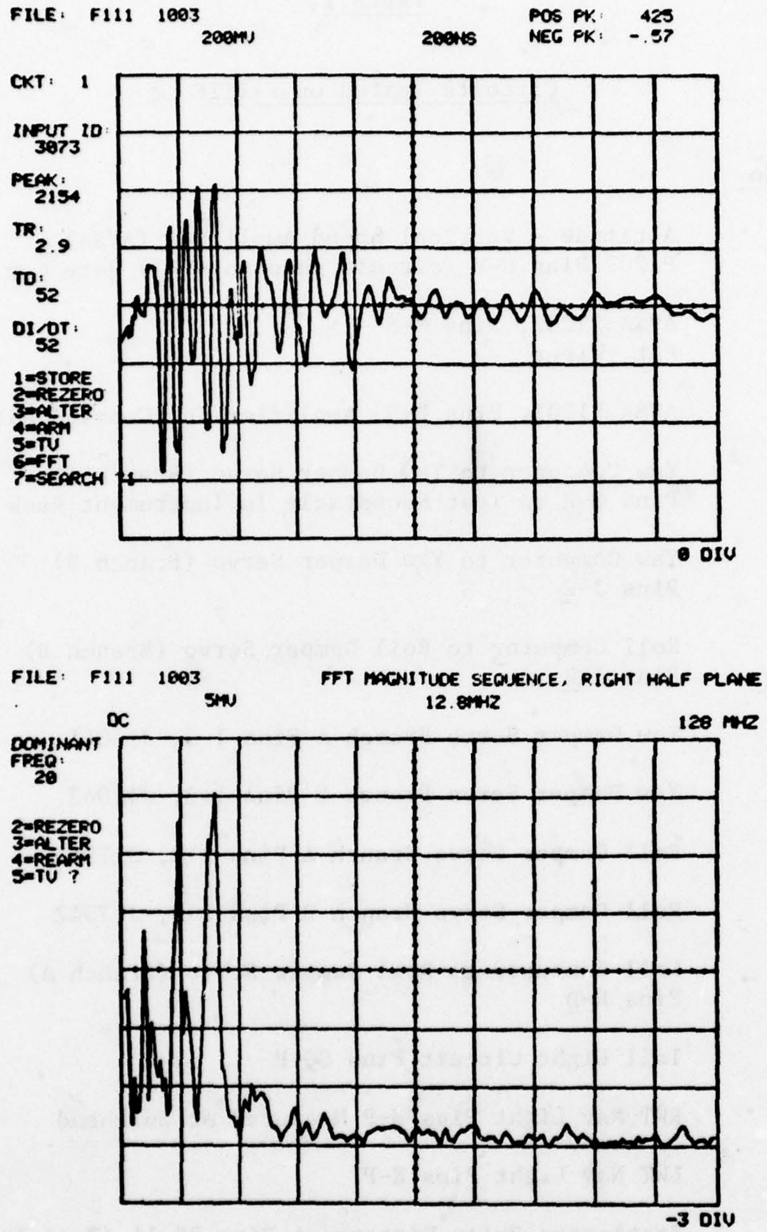
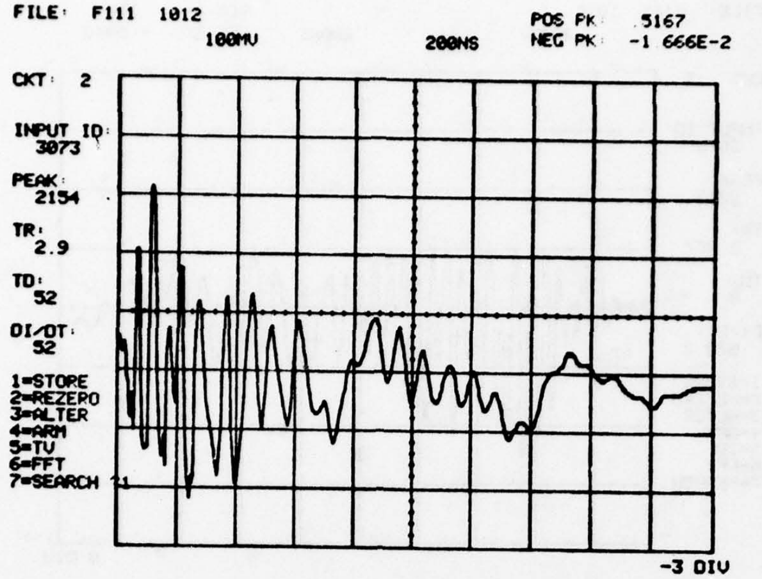


Figure 12. Induced Voltage and Frequency Spectrum Altitude-Vertical Speed Amplifier, P1202, pins U-V



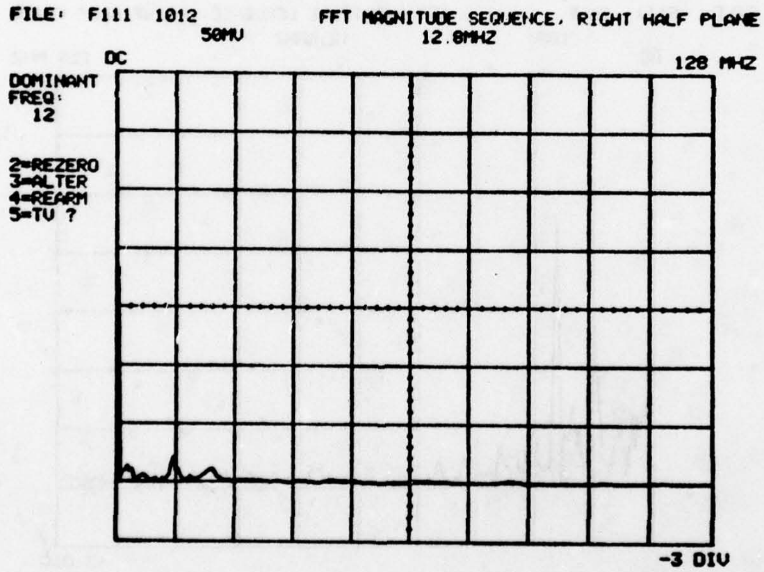
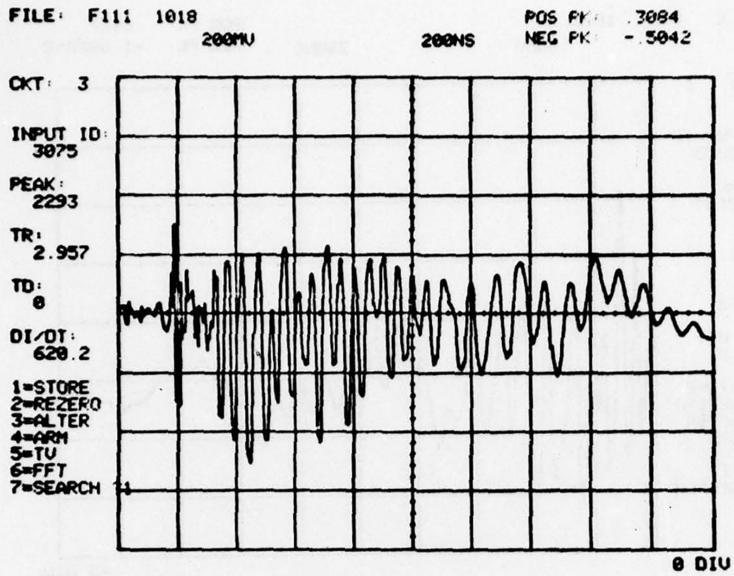


Figure 13. Induced Voltage and Frequency Spectrum
Altitude-Vertical Speed Amplifier, P1202, pins M-S



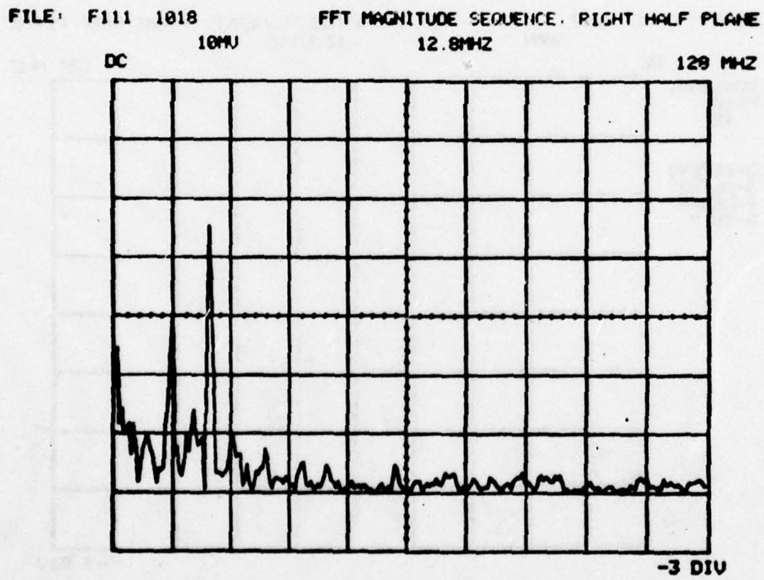


Figure 14. Induced Voltage and Frequency Spectrum Altitude-Vertical Speed Amplifier, P1201, pins B-S

The graticule of the displays can be interpreted like that of an oscilloscope. The zero reference for each graph may change from one display to the next. The number appearing at the lower right corner of the graticule indicates the location of the horizontal axis or zero reference. This number always represents the zero position with respect to the center of the graticule. For example, if "-3 DIV" is indicated, the zero reference is three divisions below the graticule center. At the top of the graticule the vertical and horizontal scale factors are displayed. In the case of Figure 12 on the top graph "200 MV" means 200 millivolts/division and "200 NS" means 200 nanoseconds/division. The "POS PK" and "NEG PK" information printed at the extreme upper right of the display represents the largest and smallest value in volts of the waveform being displayed. On the left hand side of the graph information as to the characteristics of the applied wave is given: PEAK is the maximum applied current in amperes, TR is the risetime in microseconds, TD is time to decay to half value, and DI/DT is rate of rise of the applied wave.

The lower graph on Figure 12 is the fast Fourier transform of the induced wave. The graph displays the frequency spectrum from DC to 128 megahertz, indicating the dominant frequency (highest peak) in the upper left hand corner as 20 megahertz.

The displays for the typical waveshapes of the induced voltage measured on circuits 1, 2 and 3 (Figures 12, 13 and 14) can be interpreted as described above. In addition, for the display of

each voltage, the Fourier Transform is shown. The dominant frequency of oscillation of these related circuits is either 12 MHz or 20 MHz.

The average values of induced voltages when scaled up to values at an applied current of 200 kiloamperes peak are listed in Table II. The only fair comparison of induced voltages can be made with the Yaw and Roll computer circuits. In the power off mode, the induced voltages are higher for the AVSA circuits, which originate in the same equipment bay as the Yaw and Roll computer circuits. Although the computer circuits are of greater length, this fact does not seem to influence the magnitude of induced voltage on these circuits when compared to the voltages on the shorter AVSA circuits.

5.2 Yaw and Roll Computer-Damper Servo Circuits

Circuits 4 through 11 are control circuits for the Yaw and Roll Damper Servos. The Yaw and Roll Computers are in the equipment bay covered by access door 1101. The circuits run from this bay to the damper servos in front of the vertical stabilizer under access door 4411, a length of approximately 17.2 meters. The damper servos receive signals from the flight control computers through the Feel and Trim Assembly. The Yaw and Roll Damper Servos then respectively position the rudder and ailerons.

It must be noted that circuits 4 through 11 are not separate circuits but are actually eight measurement points on four circuits. These four circuits can be further defined as two branches, A and B, on the Yaw Damper and Roll Damper circuits.

TABLE II

INDUCED VOLTAGES ON F-111E CIRCUITS EXTRAPOLATED TO FULL THREAT

Circuit	Description	Number of Measurements on Circuits	Induced Voltage at 200 KA Volts		Dominant Frequency
			Positive	Negative	
1	Altitude - Vertical Speed Amplifer (AVSA) P1202 Pins U-V, Rate Gen Out	4	46	53	20 MHz
2	Altitude - Vertical Speed Amplifier (AVSA) P1202 Pins M-S, Pow. Wiper	7	40.6	1.06	12 MHz
3	Altitude - Vertical Speed Amplifier (AVSA) P1201 Pins B-S, Amplifier In, Command Alt	6	22.4	38.7	20.5 MHz 12.5 MHz
4	Yaw Computer to Yaw Damper Servo (Branch A)	86	power off 23 power on 93	power off 28 power on 90	2.5 MHz
5	Yaw Computer to Yaw Damper Servo (Branch B) Test Receptacle, Pins J-E	13	power off 13.4 power on 59.7	power off 19.2 power on 109.1	12.8 MHz
6	Roll Computer to Roll Damper Servo (Branch B) Test Receptacle, Pins J-E	7	power off 11.4 power on 33.6	power off 9.0 power on 78.0	12.8 MHz
7	Yaw Damper Servo (Branch A) J17041, Pins 1-3	17	15.4	16.0	12 MHz
8	Yaw Damper Servo (Branch B) J17042, Pins 1-3	8	18.2	12.4	15.5 MHz
9	Roll Damper Servo (Branch A) J17041, Pins 1-3	11	11.5	15.3	12.5 MHz
10	Roll Damper Servo (Branch B) J17042, Pins 1-3	23	18.3	18.7	12 MHz

TABLE II (cont)

INDUCED VOLTAGES ON F-111E CIRCUITS EXTRAPOLATED TO FULL THREAT

Circuit	Description	Number of Measurements on Circuits	Induced Voltage at 200 KA Volts: Positive	Induced Voltage at 200 KA Volts: Negative	Dominant Frequency
11	Roll Computer to Roll Damper Servo (Branch A) Test Receptacle, Pins H-D	9	power off 32.0 power on 58	 36.5 63	11.5 MHz
12	Tail Light, Escape Capsule Disconnect Pins GG-P	71	58.0	62.8	12 MHz
13	Right Wing Position Light Escape Capsule Disconnect, Pins N-P	6	40.5	40.2	12 MHz
14	Left Wing Position Light Escape Capsule Disconnect, Pins X-P	9	44.5	30.6	12 MHz
15	Fuel Indication, Right Wing Stationary Pylon Disconnect, Pins 35-14	12	nose-to-tail 128.3 nose-to-right wing tip 226.5	 116.8 216.0	2 MHz
16	Roll Rate Gyro, Feel & Trim Assy P200, U-AA	2	16.9	24.5	2.5 MHz
17	Pitot Heater, Radome Disconnect, P1, A-B	24	6824	2627	2 MHz

Figure 15 is a diagram that simplifies an explanation as to where the measurements were made. There were a number of measurements made at each of these locations. The transient voltage levels given in Table II have been normalized to magnitudes that would be induced on the circuits by a 200 kiloampere peak current wave. This was accomplished by multiplying the measured induced voltage by the ratio 200 KA/I_{max} applied.

The measurements at the computer end were made at a test receptacle located on the front panel of the computers as shown in Figure 16. From the schematic, Figure 15, the pins on the test receptacle are monitor points for various circuits within the computer. The advantage to having this test receptacle is that no break-out cable or box is needed to make a transient voltage measurement. The shielded cable used to make the connection from the test receptacle to the fiber-optics transmitter is shown in Figure 16.

At the other end of the servo circuits, measurements were made at the damper servos with the addition in the circuits of the specific break-out cables and box. This set-up is shown in Figure 17.

The average transient voltage measured on the computer-damper servo circuits when extrapolated up to the 200 kiloampere peak threat level is listed in Table III.

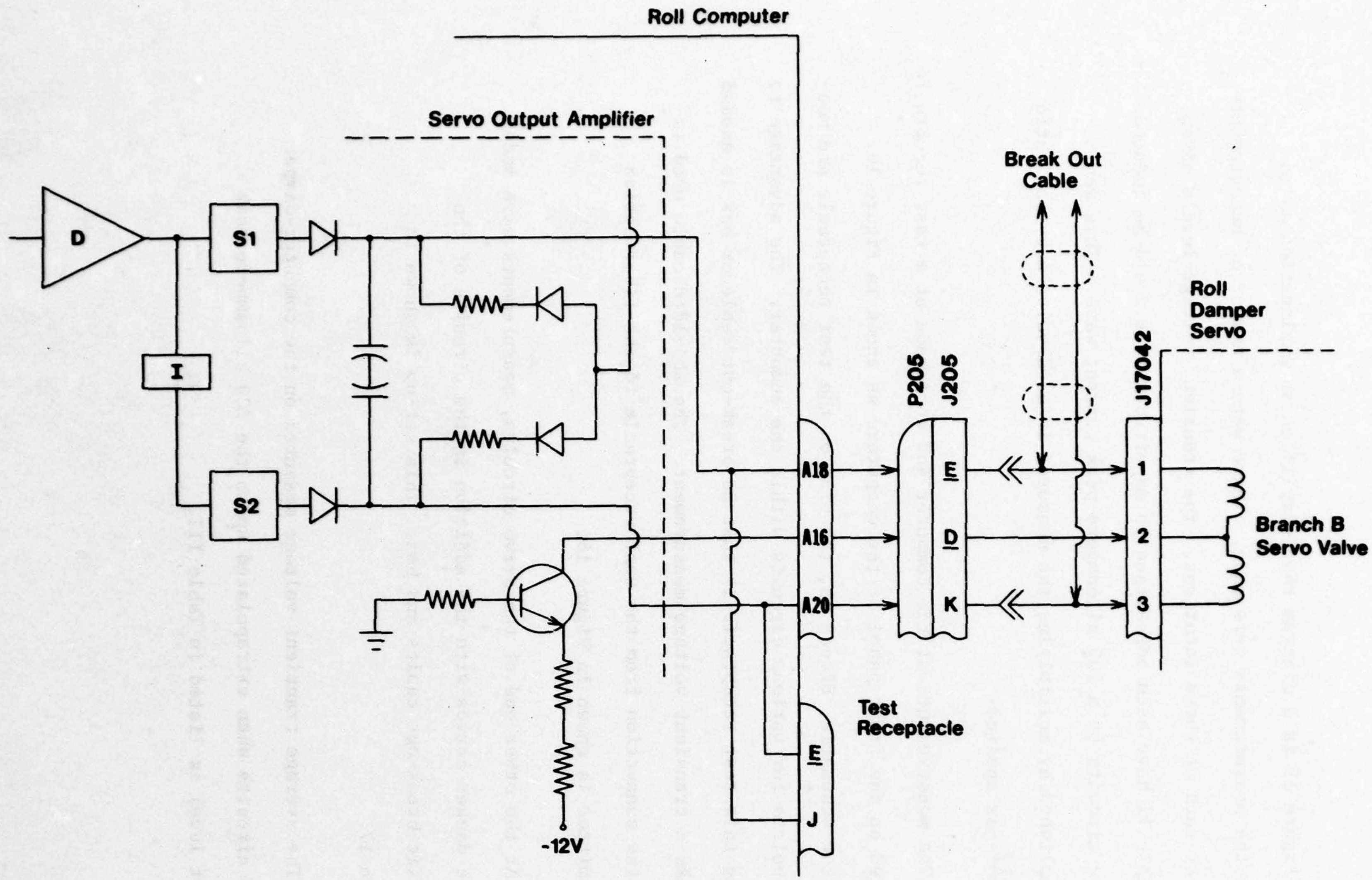


FIGURE 15

ROLL DAMPER SERVO CIRCUIT (BRANCH B)
SHOWING TEST RECEPTACLE AND BREAK OUT CABLE
USED TO MONITOR INDUCED TRANSIENT VOLTAGES

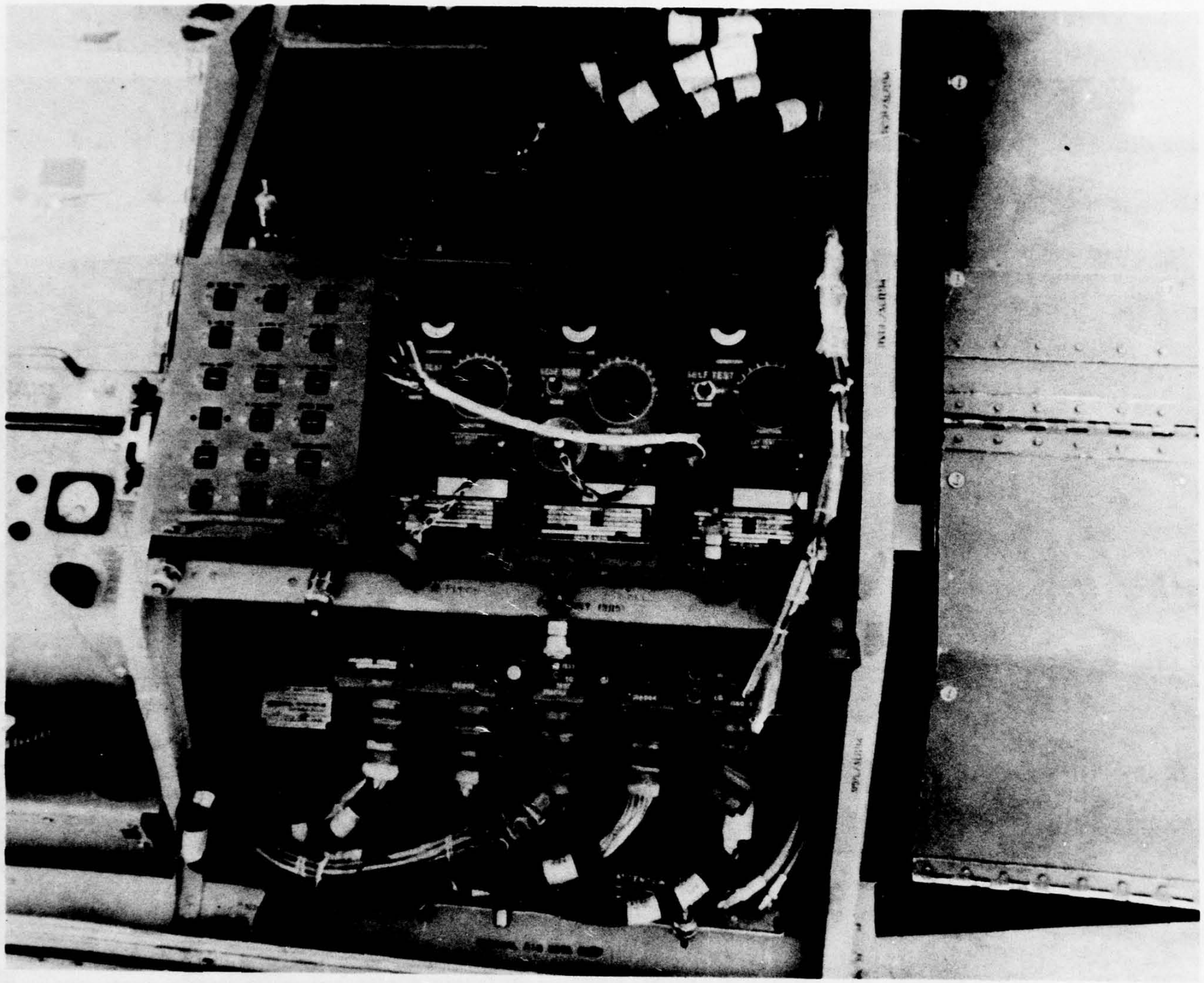


FIGURE 16

ACCESS DOOR 1101
EQUIPMENT BAY ON F-111E SHOWING
PITCH, ROLL, AND YAW COMPUTERS

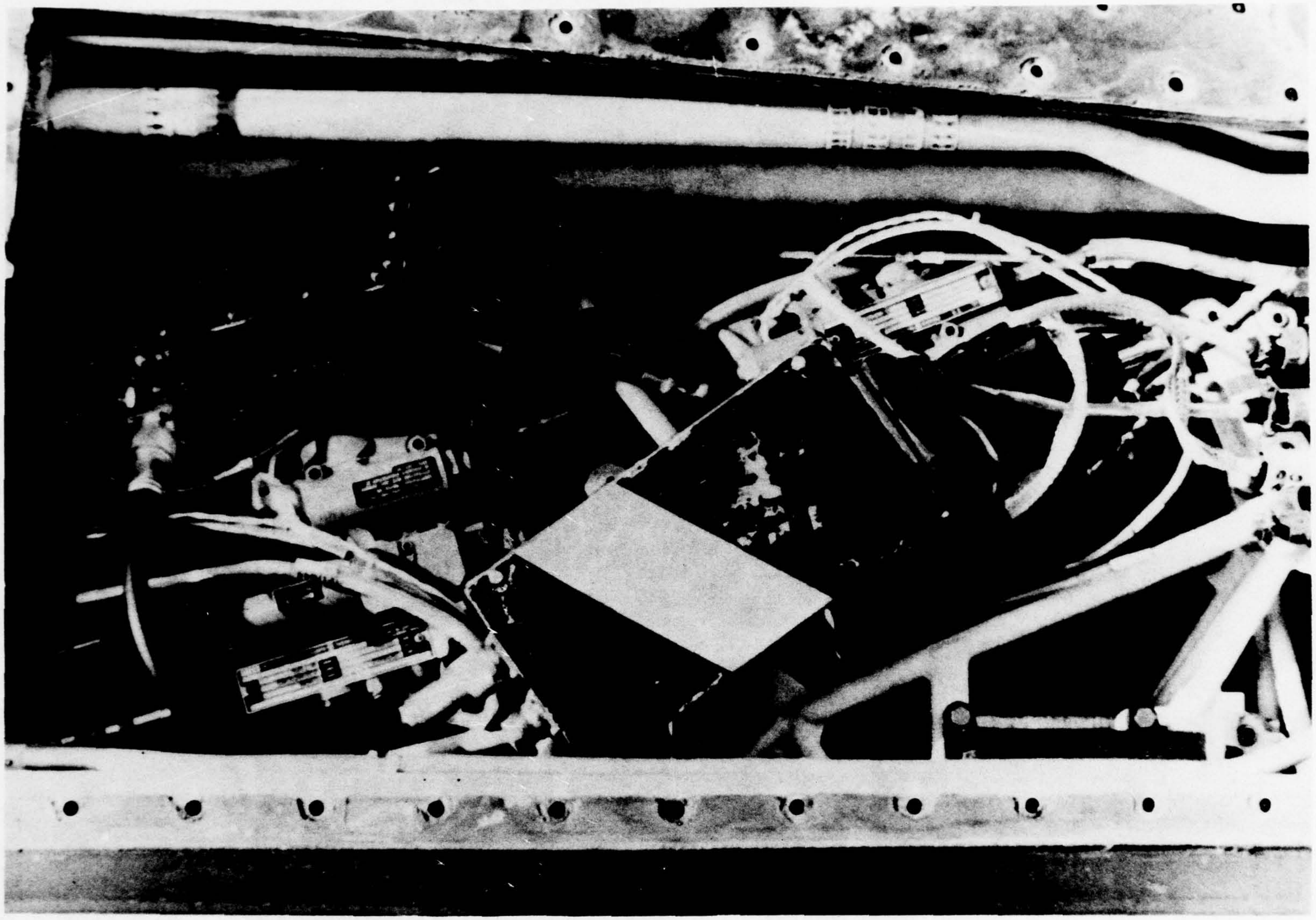


FIGURE 17

TEST CONNECTION FOR YAW
DAMPER SERVO TRANSIENT MEASUREMENT

TABLE III

Computer-Damper Circuits	
Average transient voltage levels @ 200 kiloamperes	
at computers	at servos
+ 20.0 volts - 23.0 volts	15.9 volts 15.6 volts

The waveshape of the transient voltages is a damped sinusoid with a dominant frequency of oscillation from 12 MHz to 15.5 MHz.

Figures 18 through 25 show typical induced voltages on the computer-damper servo circuits. In addition to the voltage the Fourier Transform is displayed showing the dominant frequency of oscillation of the induced voltage waveshape.

5.3 Position Light Circuits

Since position lights and navigation lights are located at the extremities of aircraft, these circuits are vulnerable to damage by lightning, because the usual points of attachment of lightning to aircraft are nose, wing tips, and tail. Also, in some cases, the light circuits have an aircraft structure return path that could lead to a substantial voltage differential built up on the circuit due to resistance of the structure. Voltages can be induced on light circuits and, also, the circuits can be damaged severely by direct attachment of lightning to the light circuits.

Measurements were made on the tail light, right wing position light, and left wing position light at the escape capsule disconnect

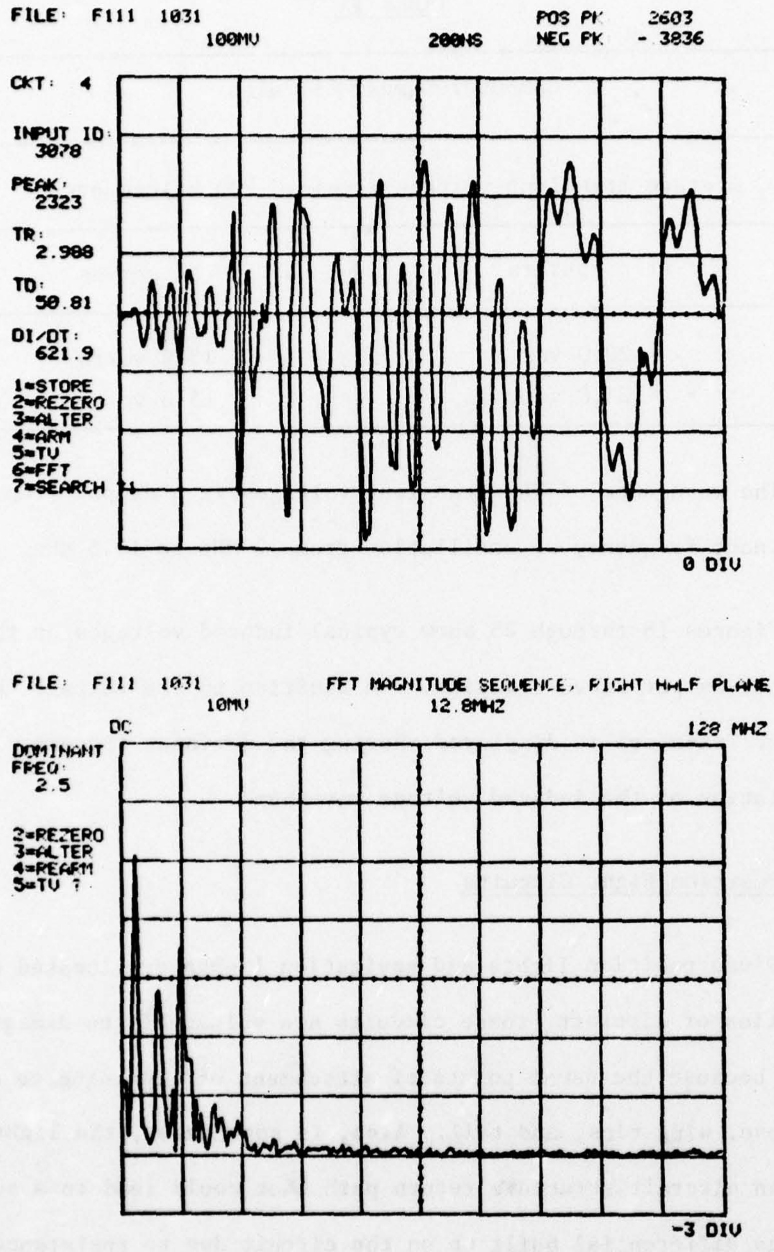


Figure 18. Induced Voltage and Frequency Spectrum
Yaw Computer, test receptacle, pins G-H, Branch A

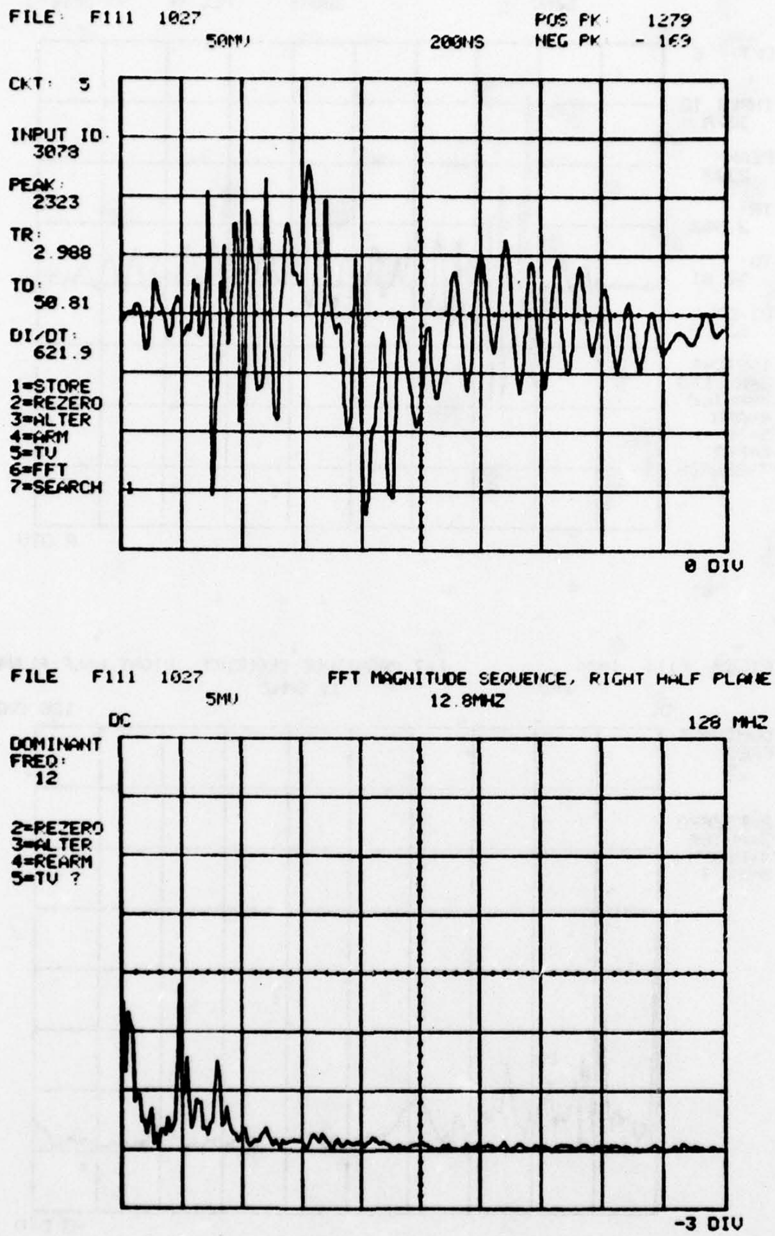


Figure 19. Induced Voltage and Frequency Spectrum
Yaw Computer, test receptacle, pins J-E, Branch B

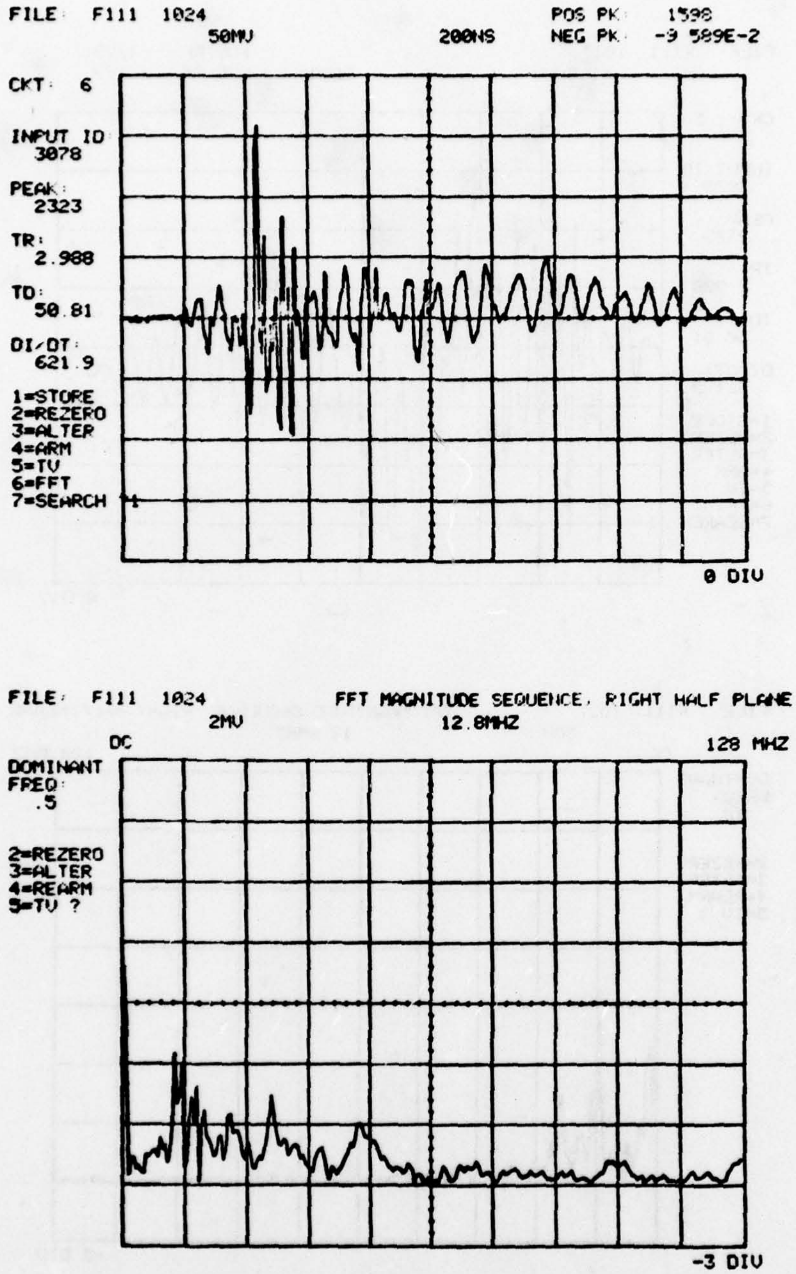


Figure 20. Induced Voltage and Frequency Spectrum
Roll Computer, test receptacle, pins J-E, Branch B

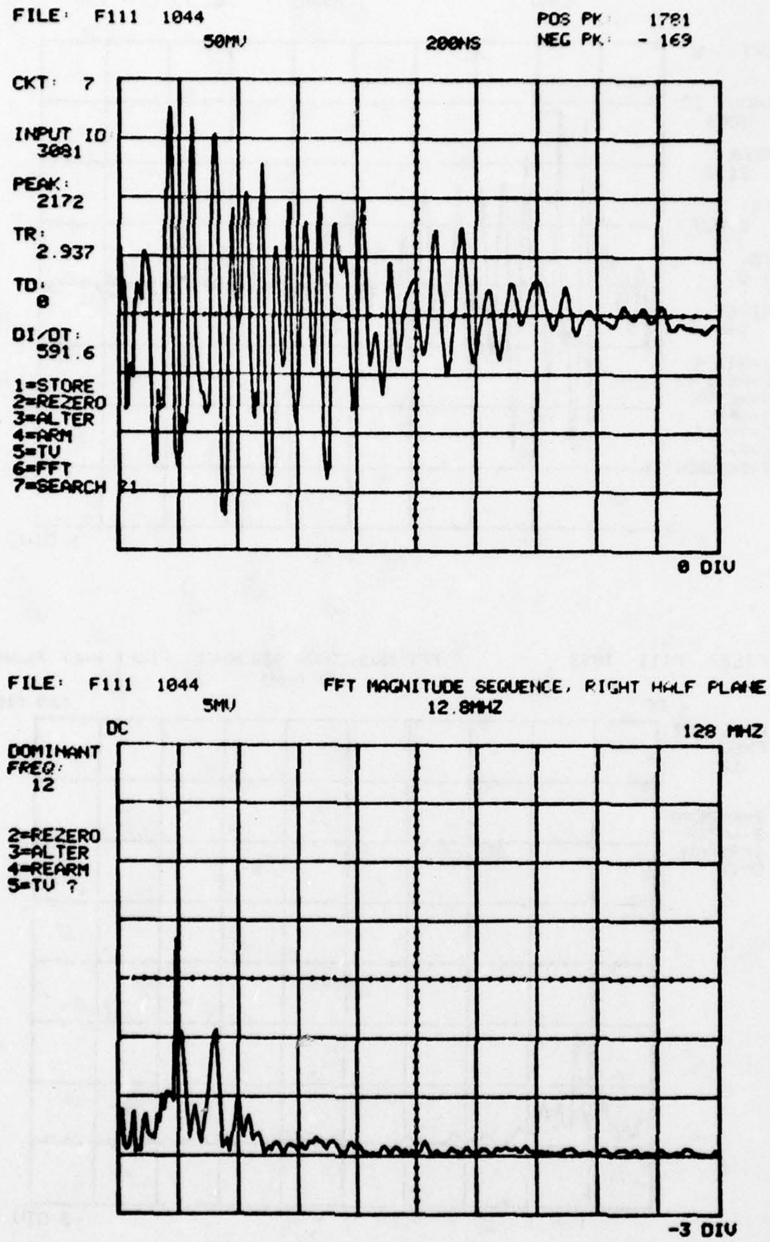
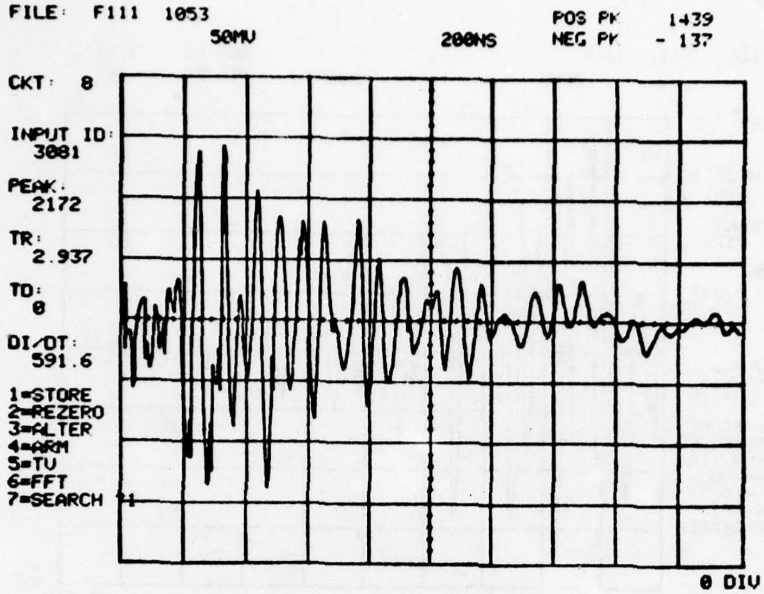


Figure 21. Induced Voltage and Frequency Spectrum
Yaw Damper Servo, J17041, pins 1-3, Branch A



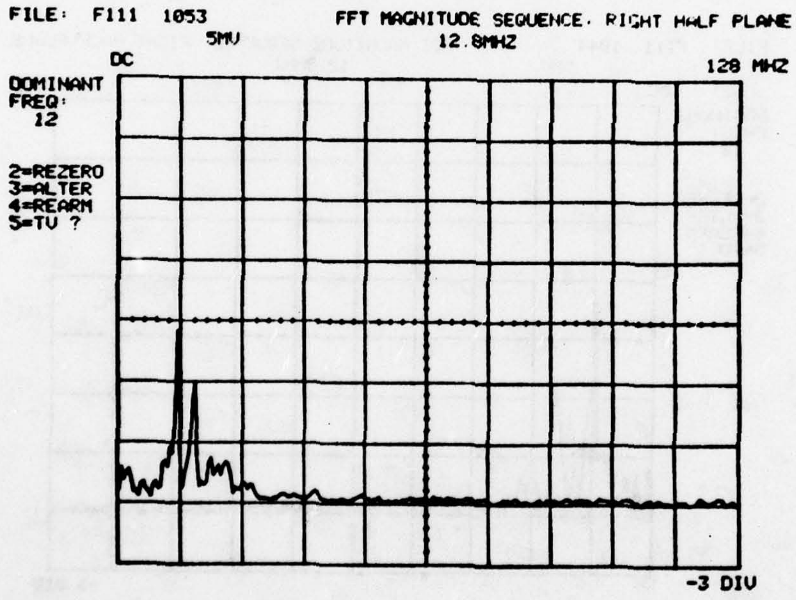


Figure 22. Induced Voltage and Frequency Spectrum
Yaw Damper Servo, J17042, pins 1-3, Branch B

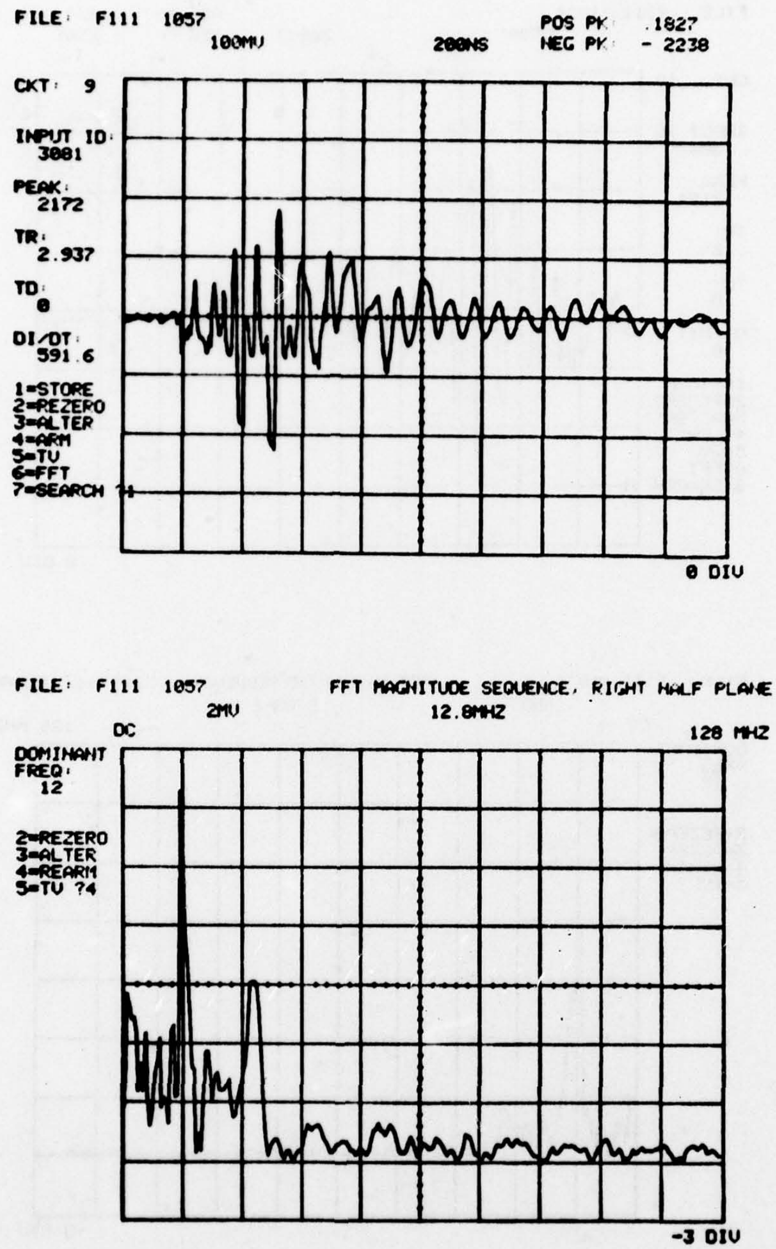
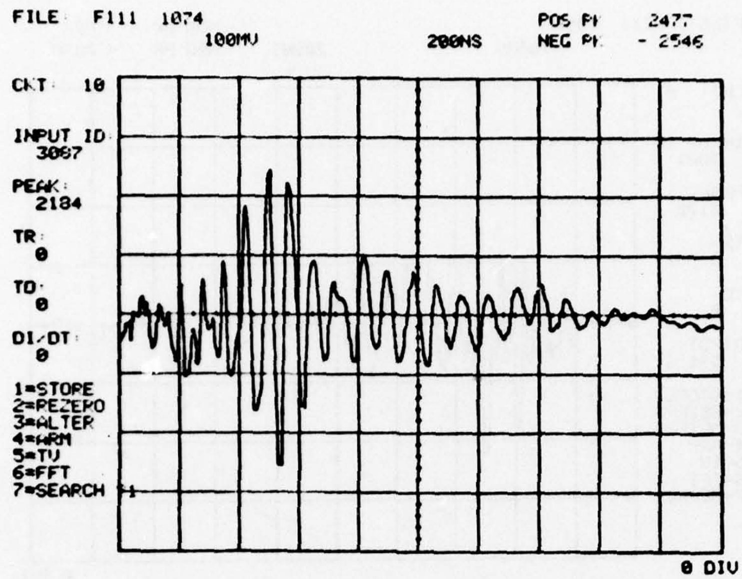


Figure 23. Induced Voltage and Frequency Spectrum
Roll Damper Servo, J17041, pins 1-3, Branch A



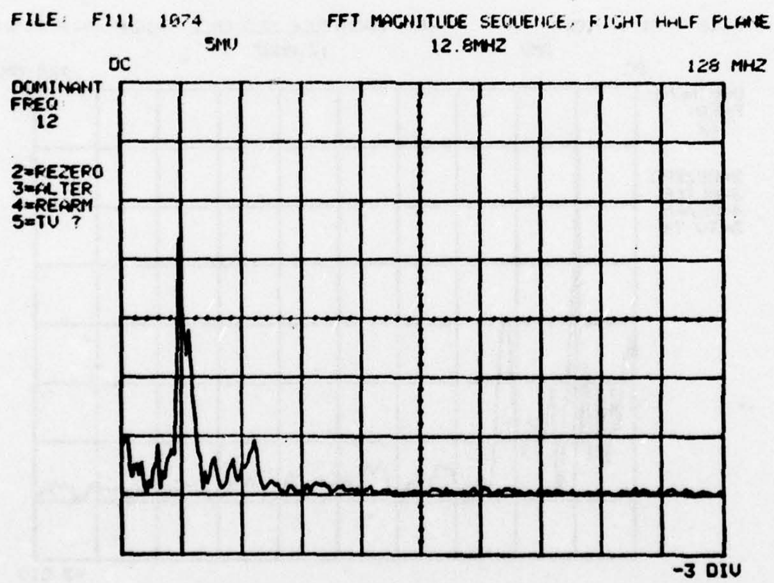


Figure 24. Induced Voltage and Frequency Spectrum
Roll Damper Servo, J17042, pins 1-3, Branch B

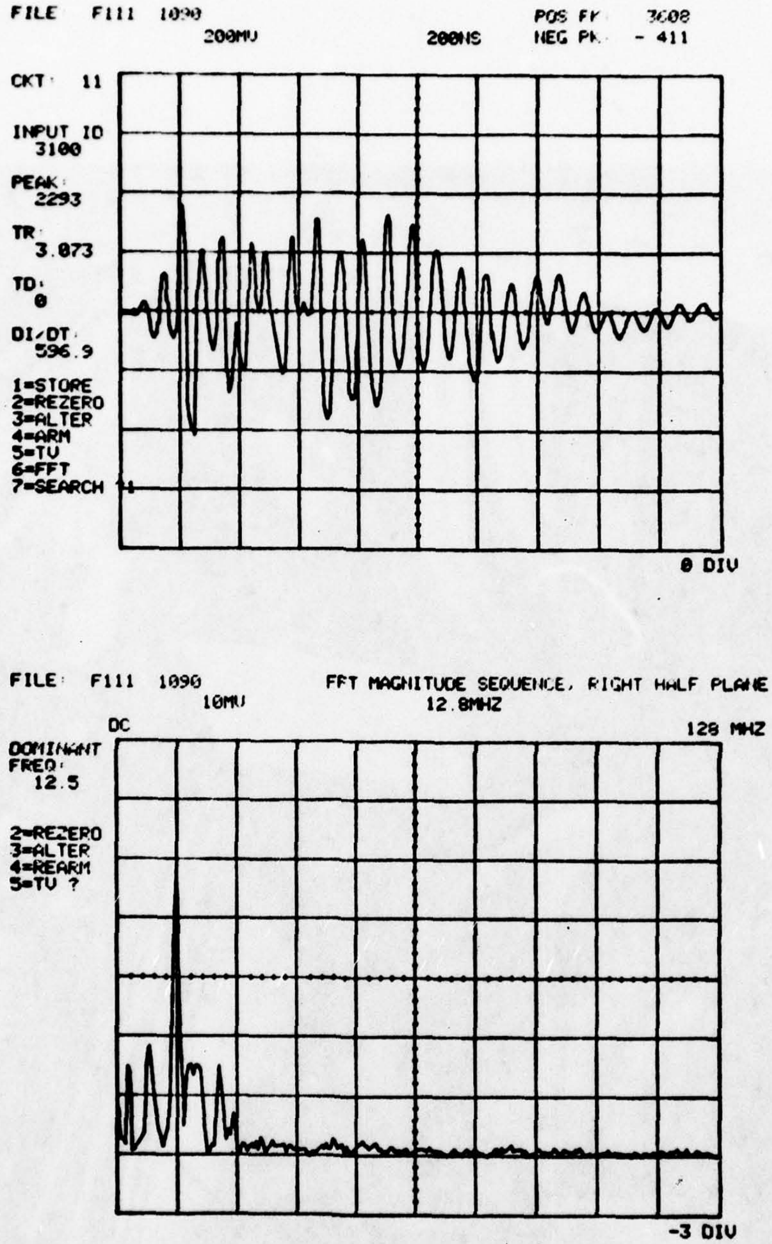


Figure 25. Induced Voltage and Frequency Spectrum Roll Computer, test receptacle, pins H-D, Branch A

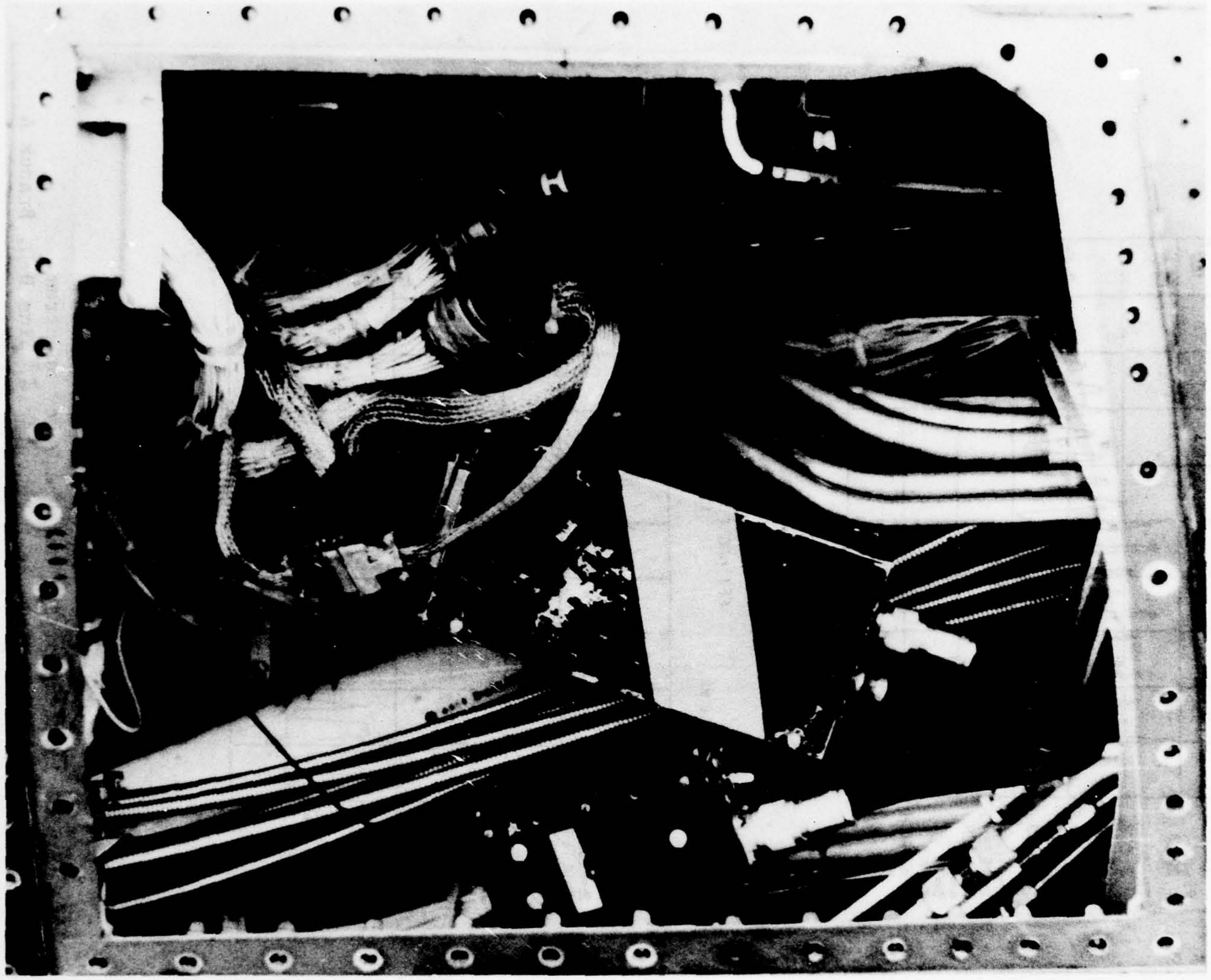


FIGURE 26

EQUIPMENT BAY COVERED BY ACCESS DOOR 1117 WHERE TAIL LIGHT AND NAVIGATION LIGHT MEASUREMENTS WERE MADE

which is located in the bay below the cockpit, reachable through access door 1117. Figure 26 shows the bay and part of the measurement system used. The light circuits are designated circuits 12, 13, and 14 and are listed in Table II, with the induced voltages measured extrapolated up to the 200 kiloampere current level. A schematic of the Position Light circuits is shown in Figure 27. An average of 46 volts was measured on these circuits with somewhat higher voltages measured on the Tail Light circuit. Examples of the transient voltage waveshapes are given in Figures 28, 29, and 30. The waveshapes are damped oscillatory with a dominant frequency of oscillation of 12 MHz.

5.4 Fuel Indication Circuit

It is a fact that a high voltage build up in a capacitive-type fuel probe can result in spark-over of the probe (Ref. 6). It is suspected that lightning strikes to aircraft have promoted arcing inside fuel tanks at the fuel probes that has caused ignition of explosive fuel-air mixtures within the tanks.

Since the amount of induced voltage on a fuel indication circuit can be important in determining whether or not the circuit and the fuel probe can promote a problem within the fuel tanks, a number of induced voltage measurements were made on the Fuel Indication circuit, measuring across the circuit at the right wing pylon disconnect. The fuel quantity measuring system is a

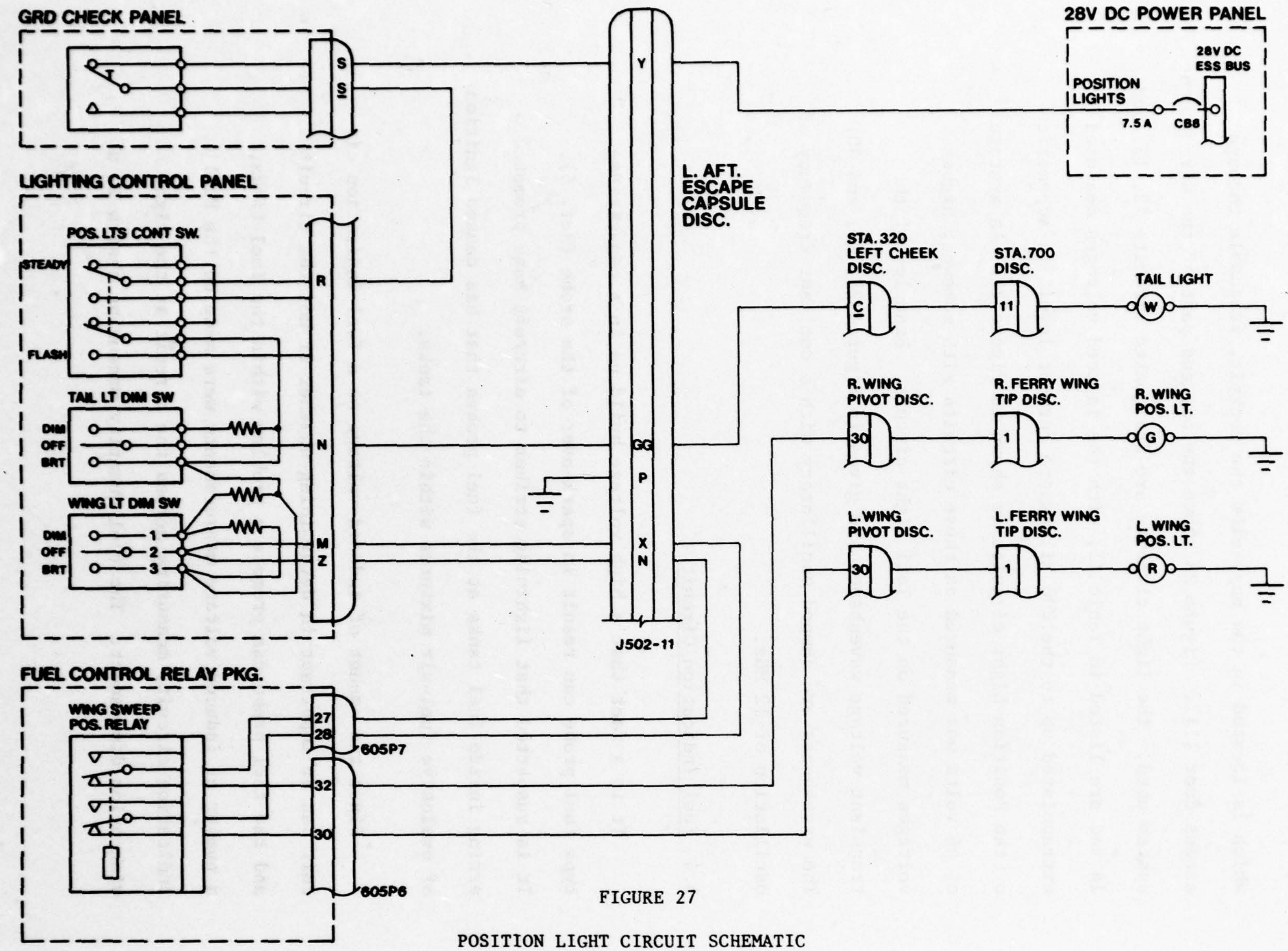


FIGURE 27

POSITION LIGHT CIRCUIT SCHEMATIC

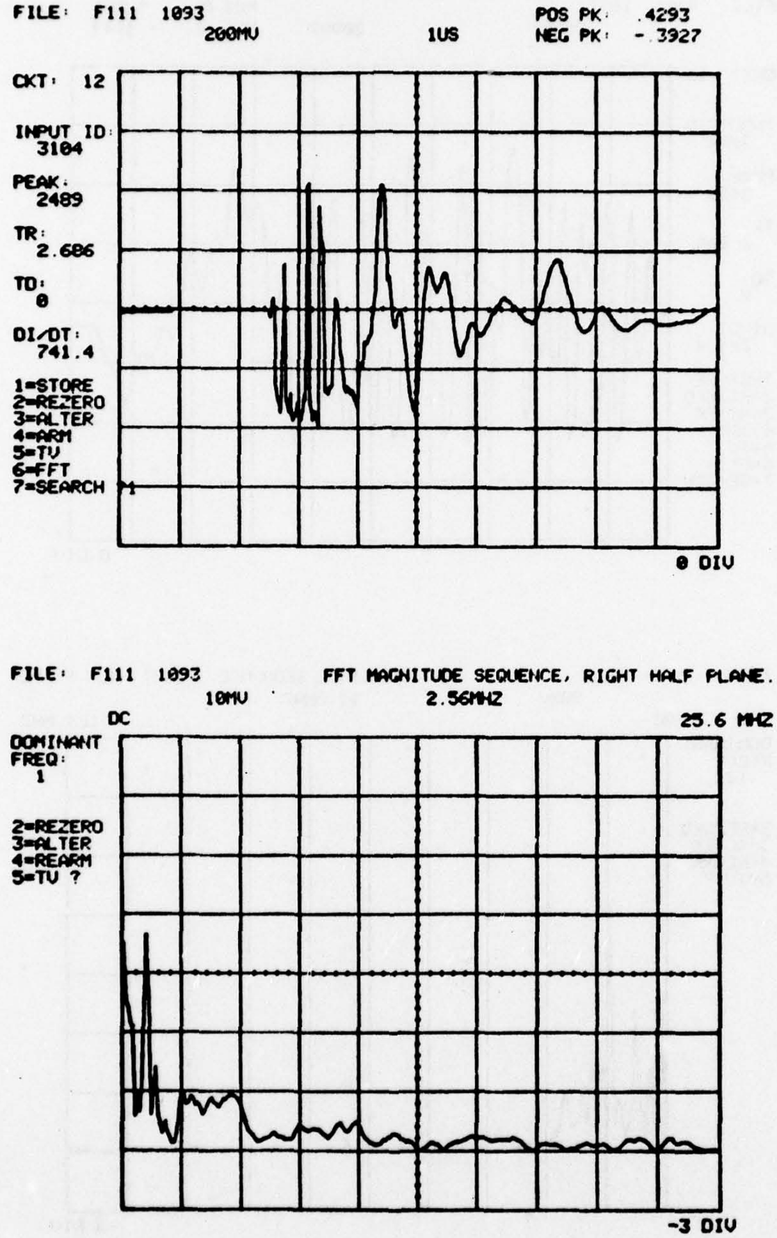


Figure 28. Induced Voltage and Frequency Spectrum Tail Light Circuit, pins GG-P

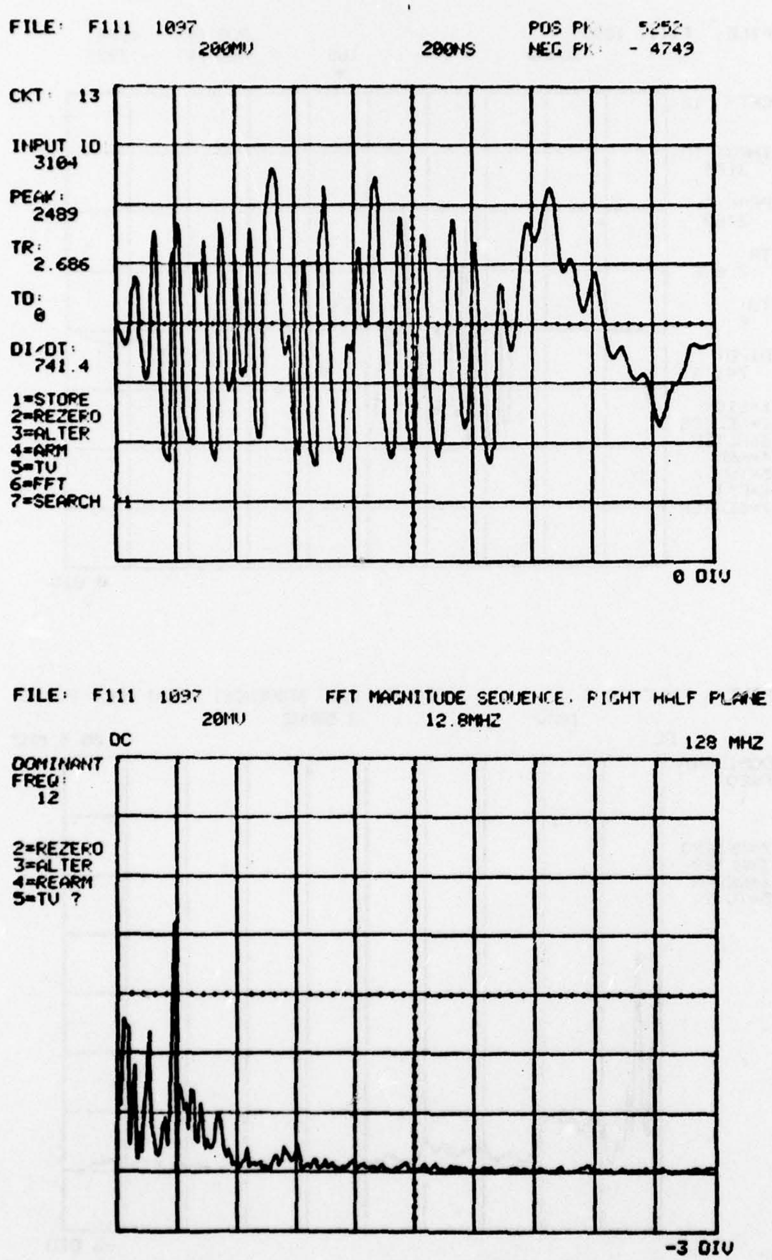
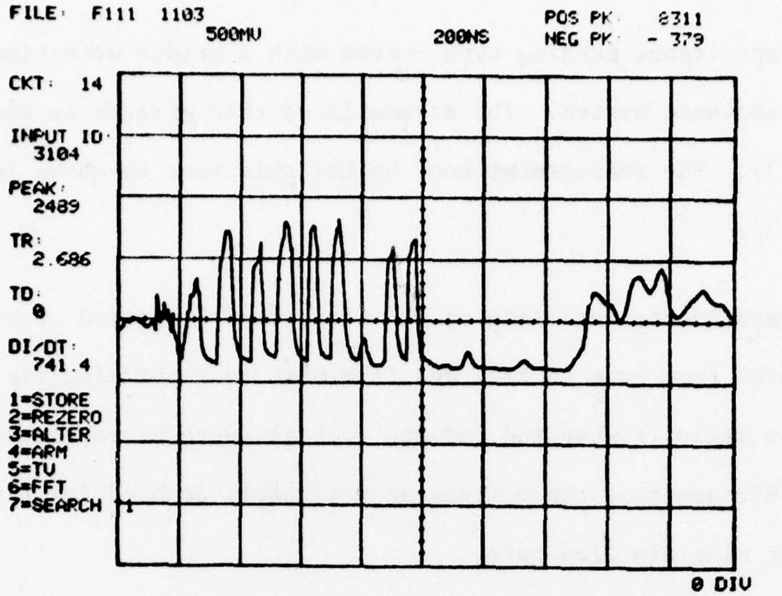


Figure 29. Induced Voltage and Frequency Spectrum
Right Wing Tip Navigation Light, pins N-P



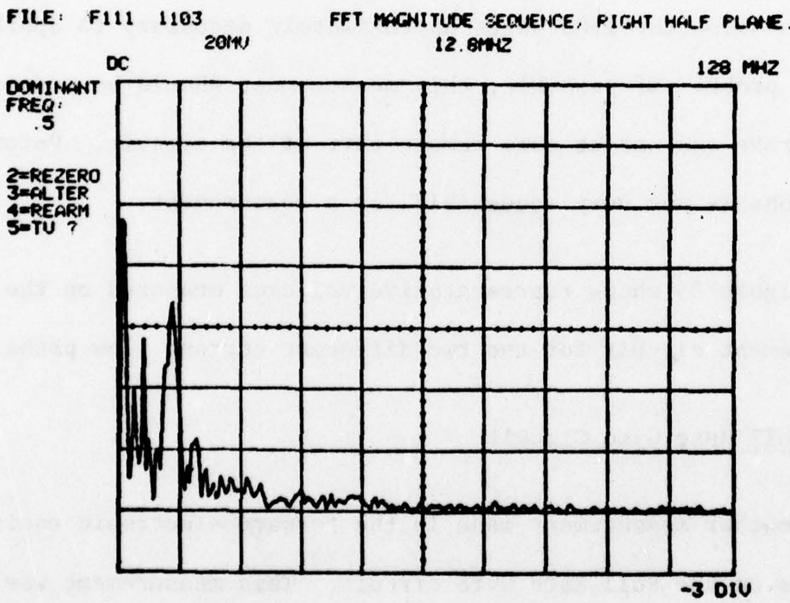


Figure 30. Induced Voltage and Frequency Spectrum Left Wing Tip Navigation Light, pins X-P

basic capacitance sensing type system with a bridge detection and servo rebalance system. The schematic of this circuit is shown in Figure 31. The measurement hook up for this test is shown in Figure 32.

Measurements were made on the circuit with applied current flow paths from nose to tail and from nose to right wing tip. As shown in Table II when the induced voltages were extrapolated up to 200 kiloamperes, the voltage approximately doubled for the nose to right wing tip flow path.

The extrapolated induced voltages did not exceed 226.5 volts. This is below the 1500 volts approximately necessary to sparkover a fuel probe. If possible, this measurement should be made at the fuel probe and not at some remote part of the circuit. Unfortunately, the probe is not very accessible for a measurement.

Figure 33 shows representative voltages measured on the fuel measurement circuit for the two different current flow paths.

5.5 Roll Rate Gyro Circuit

Another measurement made in the forward electronic equipment bay was on the Roll Rate Gyro circuit. This measurement was made at the Feel and Trim Assembly at connector P200, pins U-AA. A schematic of this circuit is shown in Figure 34. The circuit extends from the equipment bay to the main landing gear wheel well, where the gyro is located.

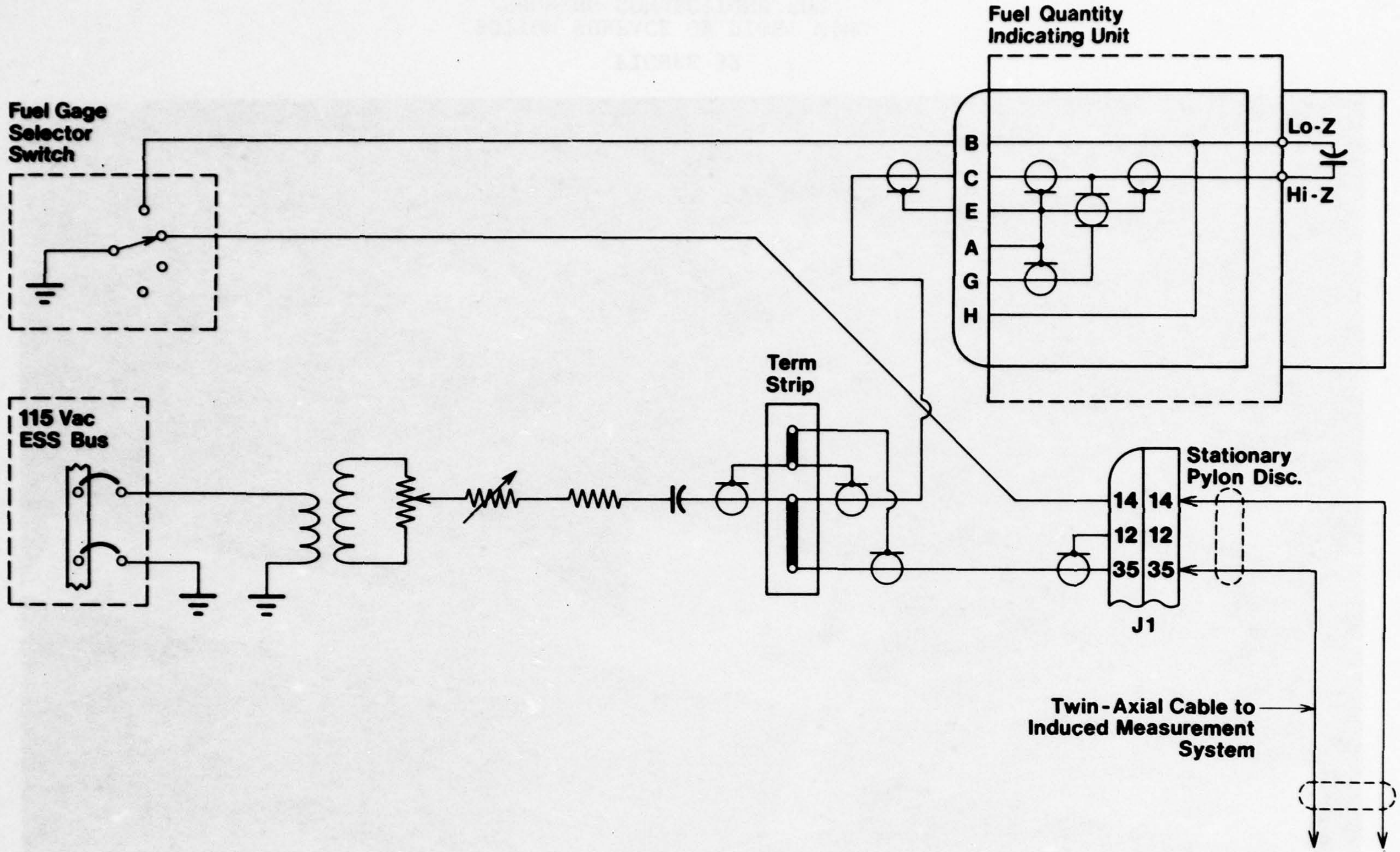


FIGURE 31

FUEL QUANTITY INDICATING SYSTEM SCHEMATIC

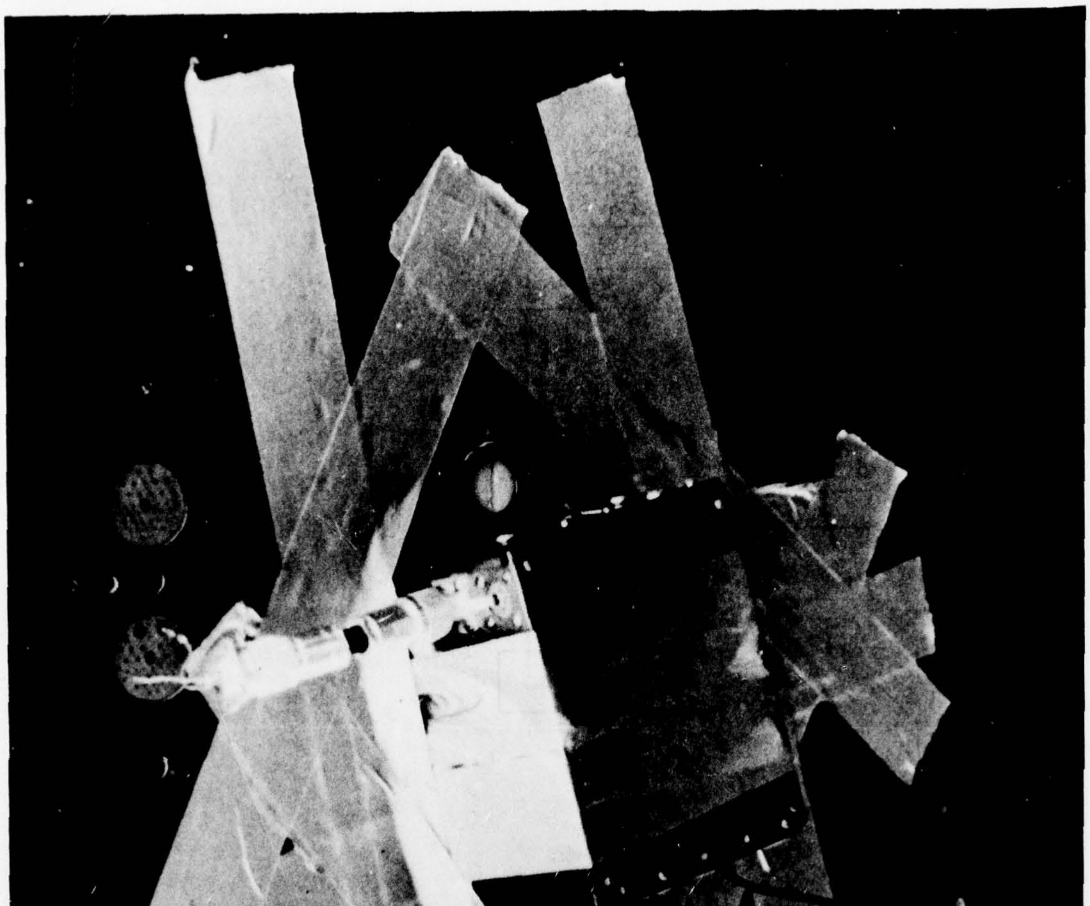
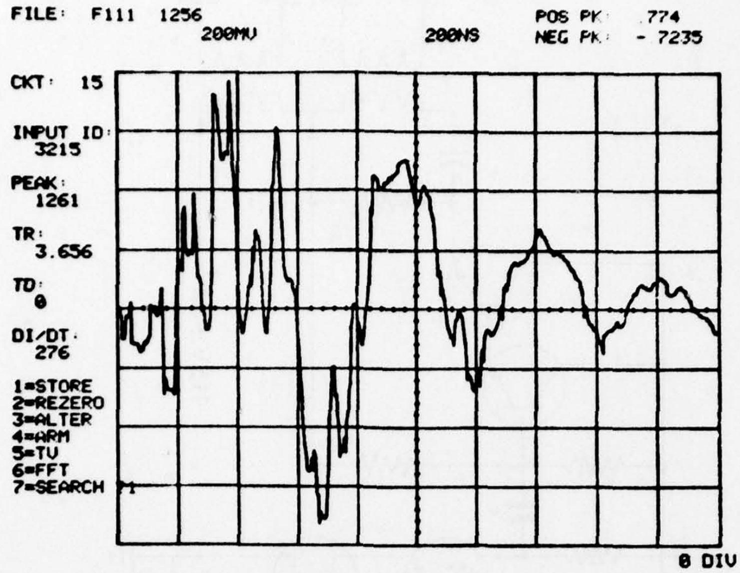
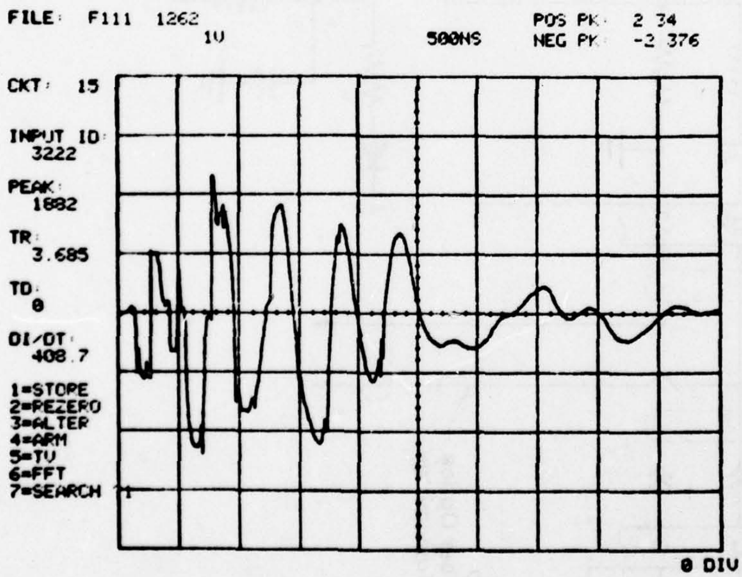


FIGURE 32
BOTTOM SURFACE OF RIGHT WING
SHOWING CONNECTIONS FOR
FUEL INDICATION MEASUREMENT



Lightning Current Path - Nose to Tail



Lightning Current Path - Nose to Right Wing Tip

Figure 33. Induced Voltage on Fuel Indication Circuit

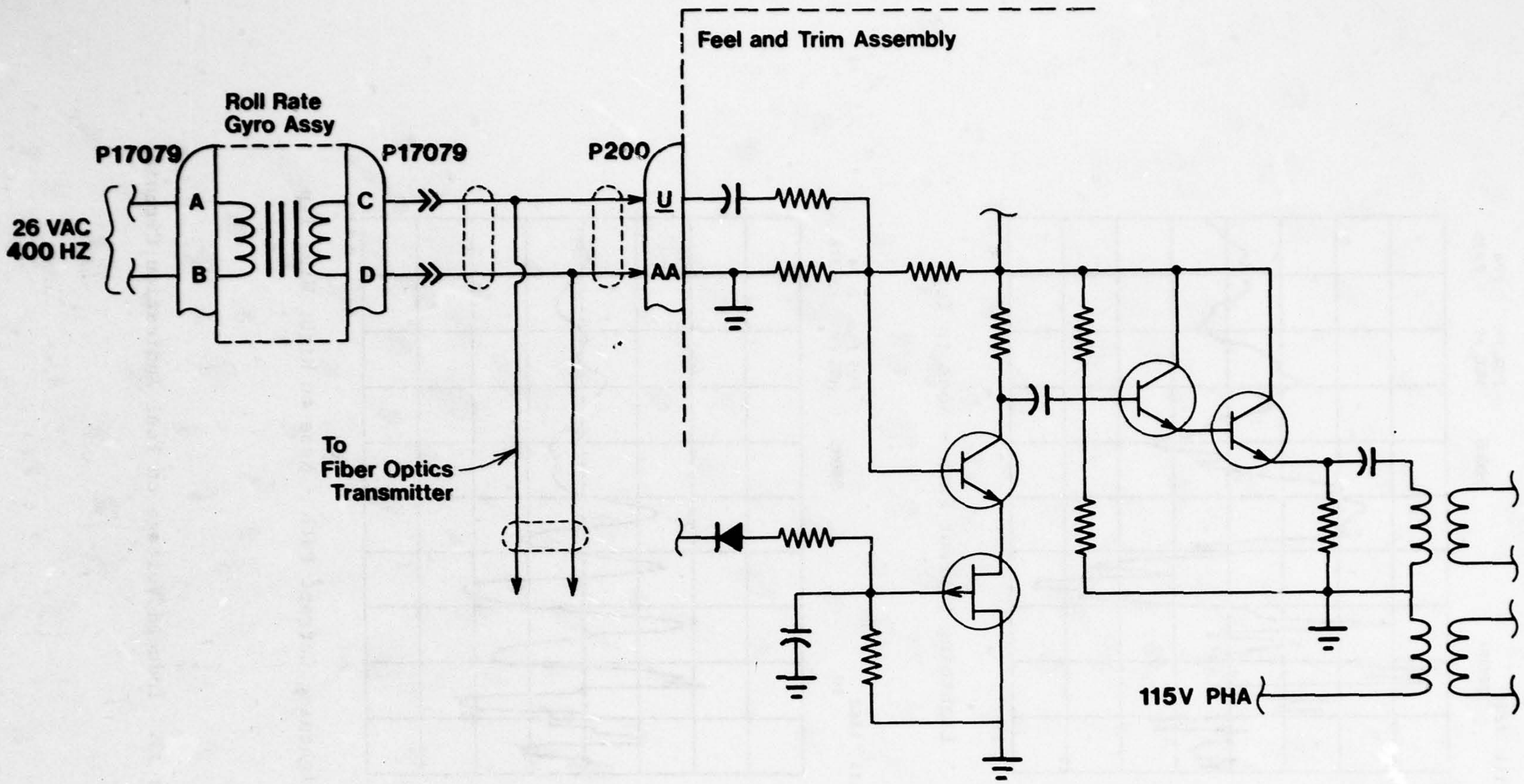


FIGURE 34

ROLL RATE GYRO
AND
ASSOCIATED FEEL AND TRIM ASSEMBLY SCHEMATIC

Rate gyros and accelerometers, in conjunction with the electronic computers and damper servo actuators, provide continuous automatic damping about the three axes of the airplane.

The number of measurements made on this circuit was minimal due to test time limitations and adverse weather conditions at the time of the test. The induced voltages when extrapolated up to the 200 kiloampere level are an average of 20 volts. This is lower than most of the other circuits tested. It is a relatively short circuit in length and the location of the circuit run within the aircraft provides minimal coupling from the lightning current flowing along the airframe. An example of the voltages measured on the Roll Rate Gyro circuit is shown in Figure 35.

5.6 Pitot Heater Transient Suppressor Tests

The pitot heater circuit on F-111E aircraft has a history of problems experienced due to lightning strikes to the aircraft. The forward position of the pitot boom makes it susceptible as an attachment point for a lightning flash. Its basic design as a thin, protruding object makes the area immediately adjacent to the boom one of high field stress concentration, promoting an attraction for lightning flash attachment.

The pitot static system provides pitot and static pressures required for operation of standby instruments, the CADC, and other

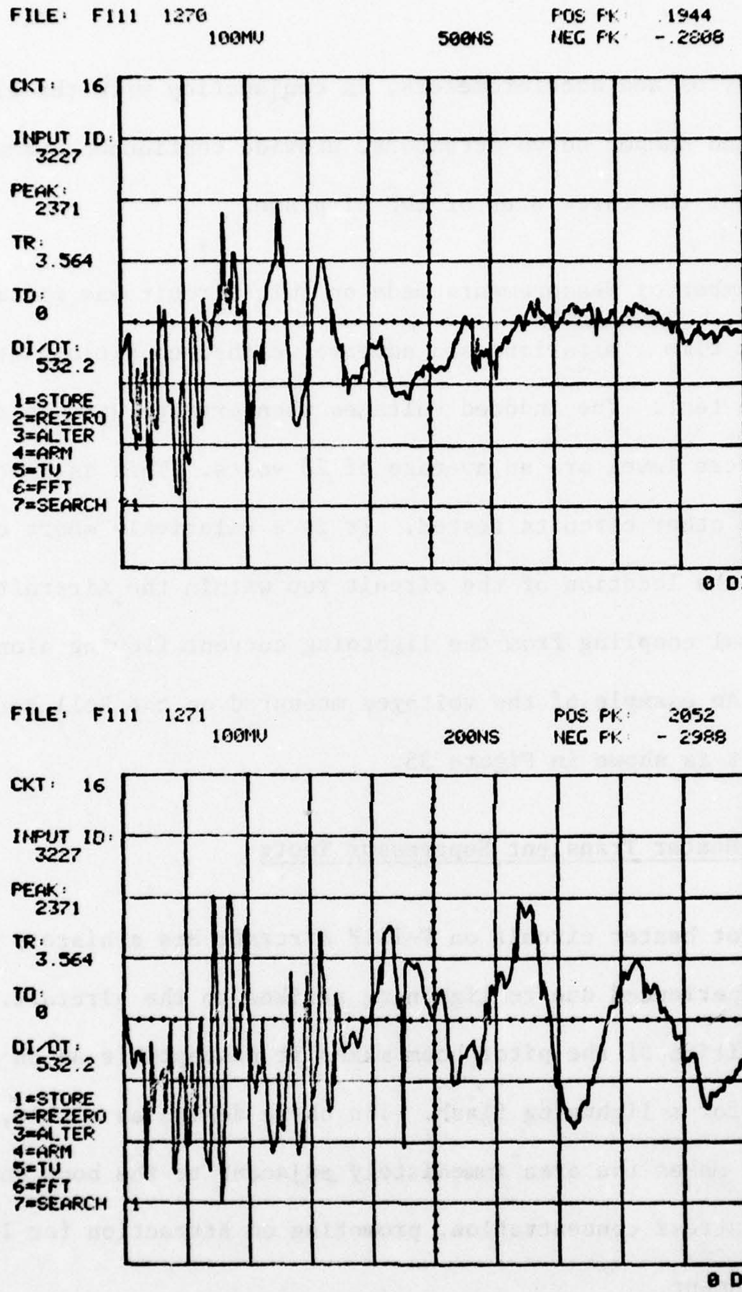


Figure 35. Induced Voltage on Roll Rate Gyro Circuit Feel and Trim Assembly, P200, pins U-AA

components. The system consists of the pitot-static tube, mounted on an adapter installed on the forward tip of the radome, and the tubing required for connection to the operating components.

The pitot heater is a heating element within the pitot tube for anti-icing. When the pitot boom gets struck by lightning, the pitot heater circuit along with the static pressure lines carries a major part of the lightning current. Damage to the pitot heater circuit has consisted of burning and destruction of the pitot heater radome disconnect plug.

Since the problem on the pitot heater circuit is clearly defined and localized at the radome disconnect, a transient protection system can be designed specifically for this circuit. One such protection system was incorporated into the pitot heater circuit and its protection capability observed.

The unprotected pitot heater induced voltages for a 200 kilo-ampere peak current wave are listed in Table II for circuit #17. The lightning suppressor evaluated for its protection of the pitot heater circuit was developed by the General Electric Company and has been tested under laboratory conditions(Ref. 7). The device is designated the DM185 suppressor and was scheduled for installation on all F-106 aircraft in 1976 as protection for the F-106 pitot heater. Since the DM185 suppressor has only been tested in the laboratory in an F-111 radome, this test series afforded an opportunity to observe the suppressor's performance on an

operational F-111E aircraft. Figure 36 shows the Pitot Heater circuit with the DM-185 suppressor in place.

RESULTS

An attempt was made to measure the transient voltage on the pitot heater circuit with power on the aircraft. When the power was turned on in the aircraft, the resistors failed in the attenuator box on the fiber optics transmitter. The 115 VAC 400 Hz overstressed the resistors and they burned out.

The fiber optics measuring system was replaced by an RG-22 twin-axial cable system utilizing a 555 Tektronix oscilloscope with a Type G differential amplifier. The measurement cable was terminated in 50 ohms at the oscilloscope. A fast rising spike was observed on the front of the Polaroid oscillograms made of the transient voltage across the Pitot Heater circuit. The magnitude of this spike is not known since the voltage trace went off the screen of the oscilloscope.

The fiber optics system was repaired and replaced the RG-22 cable system. The Tektronix digitizer was again used for data gathering and recording.

Measurements were again made on the Pitot Heater circuit without power on the aircraft, with and without the DM185 suppressor in the circuit. Table IV compares the voltages measured on the circuit with

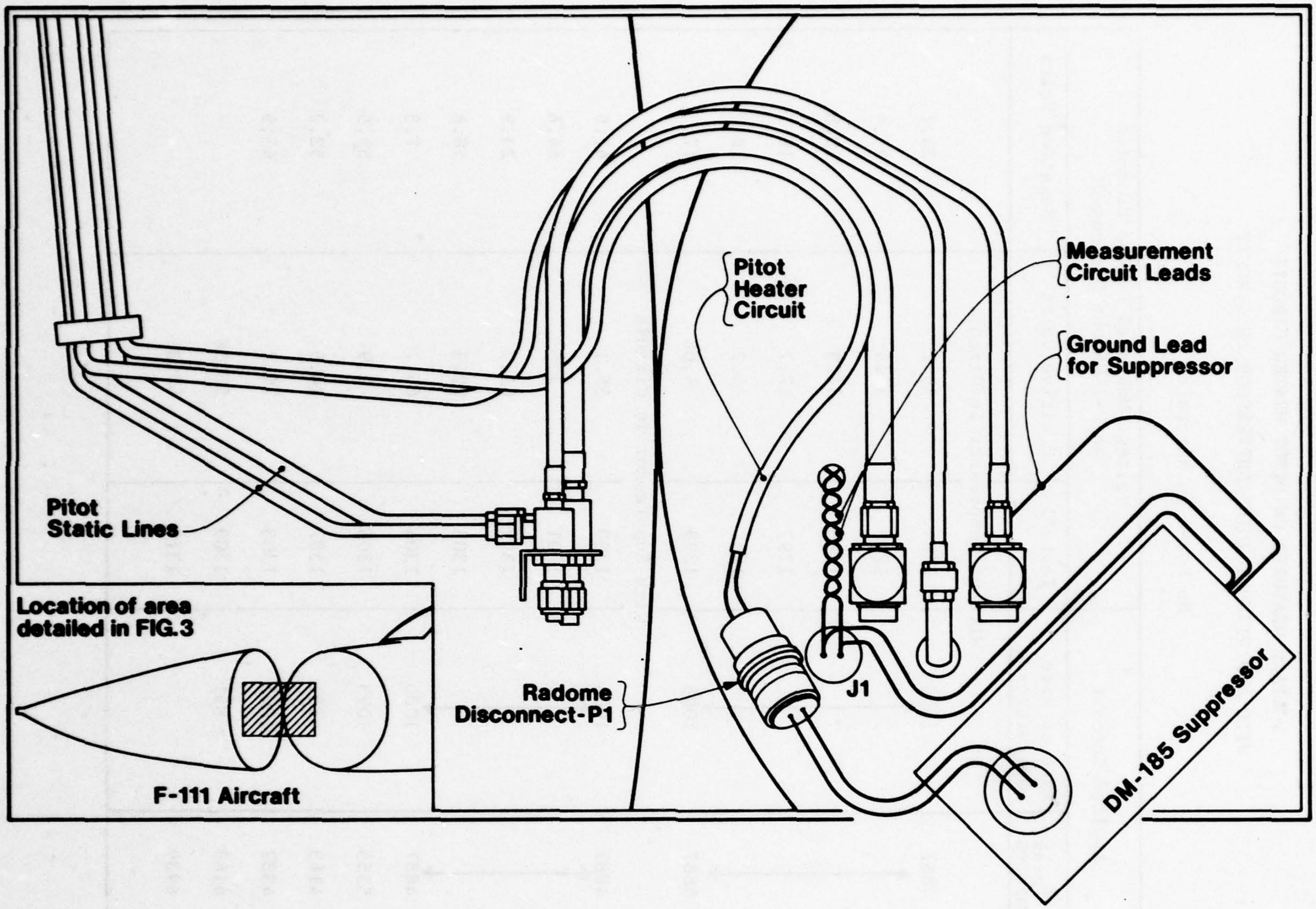


FIGURE 36

CONNECTIONS TO F-111 PITOT HEATER CIRCUIT
SHOWING DM-185 SUPPRESSOR IN CIRCUIT

TABLE IV

VOLTAGE MEASURED ON PITOT HEATER CIRCUIT
WITH AND WITHOUT DM185 SUPPRESSOR IN CIRCUIT

No Power on Aircraft

Applied Current		Voltage Measured Across Pins A-B on P-1 Radome Disconnect		
I_{peak} Amperes	Rate of Rise Amps/microsec	Test #1	Positive Volts	Negative Volts
		Without Suppressor in Circuit		
4887	1005	1294	39.2	24.7
		1295	33.4	33.4
		1296	34.8	50.8
		1297	12.7	16.7
		1298	5.7	16
4887	1005	1299	4.06	17
		With Suppressor in Circuit		
4887	1005	1300	55.1	47.9
		1301	1.5	64.6
		1302	61.7	23.9
		1303	22.5	58.8
4887	1005	1304	66.7	7.3
5355	1093	1305	2.9	59.5
4163	851	1307	14.5	52.2
4887	1005	1308	76.2	43.9
4163	851	1309	56.58	
6939		1310	65.3	

and without the suppressor in the circuit. As shown in the table, comparisons can be made at an applied current peak amplitude of 4887 amperes with a 3.89 microsecond rise time on the front of the wave.

Due to the limited extent of the information obtained from the voltages measured, it can not be clearly ascertained whether or not the suppressor was operating to its designed capabilities. At the applied current levels that the aircraft was subjected to, the maximum voltages present on the pitot heater circuit were on the order of 50 to 70 volts. This voltage level is approximately where the DM185 suppressor chops the transient voltage according to Reference 7. The applied current was increased to 6939 amperes peak with a 5.2 microsecond rise time and the voltage observed on the circuit was still within the 50 to 70 volt range.

Due to tests being done on an operational aircraft, the applied current was not increased so as not to promote damage to the aircraft electrical circuitry.

Therefore, the transient voltage was not increased to a high enough level to clearly show a voltage limiting effect.

The transient voltage waveshape did change when the suppressor was placed in the circuit. Figure 37 shows the transient voltage on the circuit with and without the suppressor. In both cases there was a fast rising spike at the beginning of the transient. The transient voltage on the circuit without the suppressor had a long duration

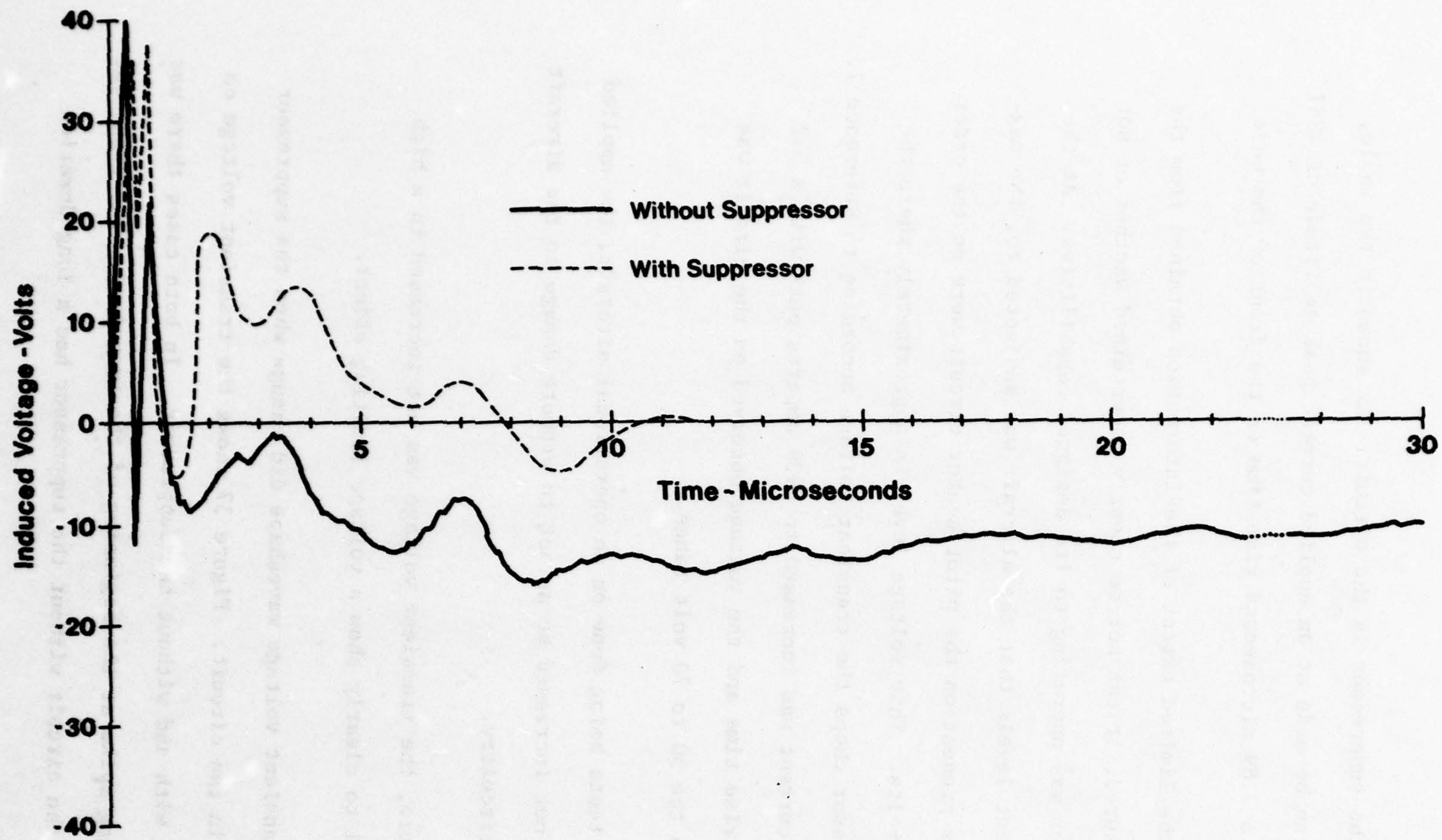


FIGURE 37

TRANSIENT VOLTAGE ON PITOT HEATER CIRCUIT P1,
RADOME DISCONNECT, PINS A-B,
WITH & WITHOUT DM 185 SUPPRESSOR IN CIRCUIT

component of approximately 15 volts magnitude and lasting up to 35 microseconds. With the suppressor in the circuit, a voltage spike was observed at the beginning, followed by a decay of the transient to zero in 15 microseconds.

It is noted that for a severe lightning stroke of 200 kiloamperes peak magnitude the transient voltage lasting 35 microseconds would have a value of approximately 600 volts.

5.7 Additional DM185 Suppressor Tests

Additional evaluation tests of the DM185 suppressor were made on another F-111 aircraft at Wright-Patterson AFB, Ohio. This aircraft is non-operational and could, therefore, be subjected to simulated lightning currents of higher magnitude. The test set-up and procedure were similar to the Eglin AFB tests.

Peak current magnitudes ranged from 11.6 to 18 kiloamperes. Table V compares the voltages measured on the Pitot Heater circuit with and without the DM185 suppressor in the circuit. All of the measurements listed were made with power off on the circuit. To simulate a power-on condition with a complete circuit to the 115 VAC bus, an inductor coil was placed across the Pitot Heater circuit in access door 1201, the bay behind the radome bulkhead.

The waveshape of the transient voltages was a damped oscillation, lasting approximately 3 microseconds. In the case of the non-protected circuit, the dominant frequency of the transient was 10

megahertz. With the suppressor in the circuit the dominant frequency was 3 megahertz.

With the higher applied lightning current there is evidence of the transient voltage on the pitot heater circuit being of a lower magnitude with the DM185 suppressor in the circuit. Also, higher frequency transients are subdued, probably due to the inductive properties of the suppressor.

From Table V the maximum transient voltage on the circuit is reduced by an average of 52% with the suppressor in the circuit. If the voltages measured at the applied current levels were extrapolated to values obtained at peak lightning currents of 200 kiloamperes, the maximum voltage on the unprotected circuit would be 2000 volts. With the suppressor in the circuit the average maximum voltage would be 920 volts.

On the basis of the information obtained during this test effort, the following conclusions can be made:

1. The DM185 suppressor can be placed in the pitot heater circuit with minimum modification of the circuit path.

2. The suppressor does reduce the level of transient voltage on the circuit.

3. No definite cut-off voltage due to the suppressor was observed on the oscillograms of the transient voltages.

TABLE V

ADDITIONAL VOLTAGE MEASURED ON PITOT HEATER CIRCUIT WITH AND WITHOUT DM185 SUPPRESSOR IN CIRCUIT

No Power on Aircraft

Applied Current		Voltage Measured Across Pins A-B on P-1 Radome Disconnect		
I_{peak} Kiloamps	Rate of Rise Amps/Microsec	Test #	Positive Volts	Negative Volts
		Without Suppressor in Circuit		
11.6	1575	1327	120	110
		1328	135	112
		With Suppressor in Circuit		
		1329	60	78
		1330	45	100
		1331	37	120
11.6	1575	1332	65	78
		Without Suppressor in Circuit		
12.2	1600	1334	115	115
12.2	1600	1335	127	115
		With Suppressor in Circuit		
13	1860	1336	72	75
12.5	1643	1337	65	88
15	1656	1338	86	68
16.2	1660	1339	78	90
16.3	1665	1340	75	95
18	1690	1341	80	100

TABLE V (cont)

ADDITIONAL VOLTAGE MEASURED ON PITOT HEATER CIRCUIT
WITH AND WITHOUT DM185 SUPPRESSOR IN CIRCUIT

No Power on Aircraft

Applied Current		Voltage Measured Across Pins A-B on P-1 Radome Disconnect		
I_{peak} Kiloamps	Rate of Rise Amps/Microsec	Test #	Positive Volts	Negative Volts
Without Suppressor in Circuit				
18	1690	1342	128	90
Without Suppressor; with coil in circuit				
12.5	1643	1343	150	115
↑	↑	1344	150	110
With Suppressor; with coil in circuit				
		1345	75	78
		1346	50	89
		1347	55	90
↓	↓	1348	65	86
12.5	1643	1349	58	90

SECTION VI

INDUCED MEASUREMENTS MADE WITH POWER ON THE AIRCRAFT

In the interest of obtaining data on an actual operation system, additional induced measurements were made on circuits other than the pitot boom with power applied to the aircraft.

Power on measurements were made on circuits #4, #5, #6 and #11. These are all damper servo circuits with the circuit extending from the yaw or roll computer to the designated servo coil. The computers require 28 VDC power and associated equipment such as the Feel and Trim Assembly requires 26 VAC to operate.

Circuit #4 is the Yaw Servo circuit measured at the yaw computer. With power on, the transient observed on this circuit was a 2 MHz damped oscillation with a duration of 2.5 microseconds (Figure 38). Also observed was a 0.3 MHz oscillation of relatively long duration. When all power-on measurements made on the damper servo circuits were compared, it was found that this 0.3 MHz oscillation was present on each circuit. On further comparison with power-off measurements, it was discovered that the 0.3 MHz oscillation exists on the power-off measurements, but at a lower magnitude. The peak to peak magnitude of this oscillation varies for each circuit but in all cases increases with power on.

Since this 0.3 MHz oscillation exists on both power-on and power-off measurements, it must be assumed that this is a circuit parameter that is present with power on or off. From Figure 15 a component

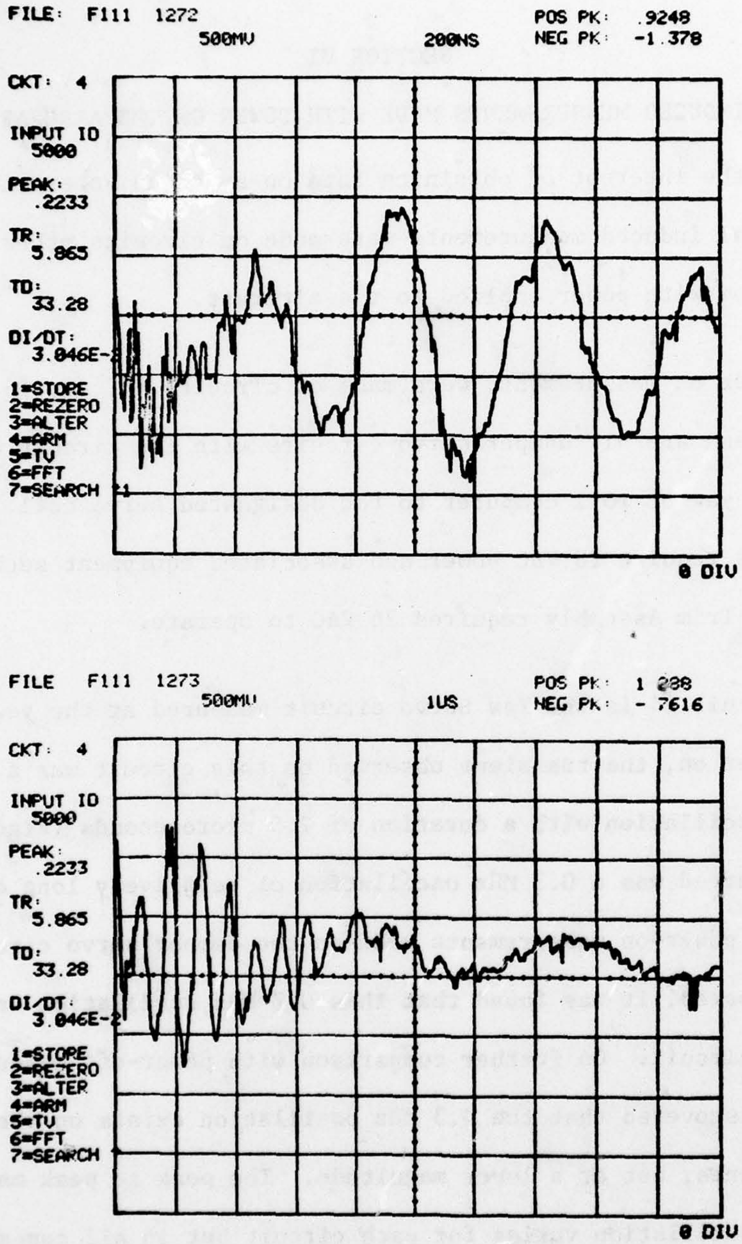


Figure 38. Induced Voltage on Yaw Computer, Power On test recteptacle, pins G-H, Branch A

that is in the circuit at all times is the damper servo coil. It is possible that the 0.3 MHz oscillation observed on the circuit is a result of the inductance of the coil under transient conditions. Table II lists the comparison of power off and power on measurements. In general the transient voltages increased in magnitude by an average of four to five times from power off to power on measurements.

The majority of measurements made using the transient analysis test technique are with power off on the aircraft. It is recognized that in some cases this results in measurements being taken on incomplete or open circuits. This is taken into consideration when analyzing data. From the power on measurements made on the F-111E servo circuits, there is a possibility that power off measurements may be conservative. Caution should be used in making this assumption since power on measurements were made only on one type of circuit, Damper Servo, of the F-111E and an increase in transient voltage with power on could be peculiar to this circuit. However, where comparisons could be made of transient voltages with power on and off from previous tests of other aircraft (Ref. 2 and 8), the trend is to higher transient voltage levels with power on.

SECTION VII

VARIOUS GROUNDING CONFIGURATIONS

An exercise in changing the aircraft ground point was done to observe what effect this change has on the induced voltage measured on a particular circuit. Figure 39 shows the various ground configurations

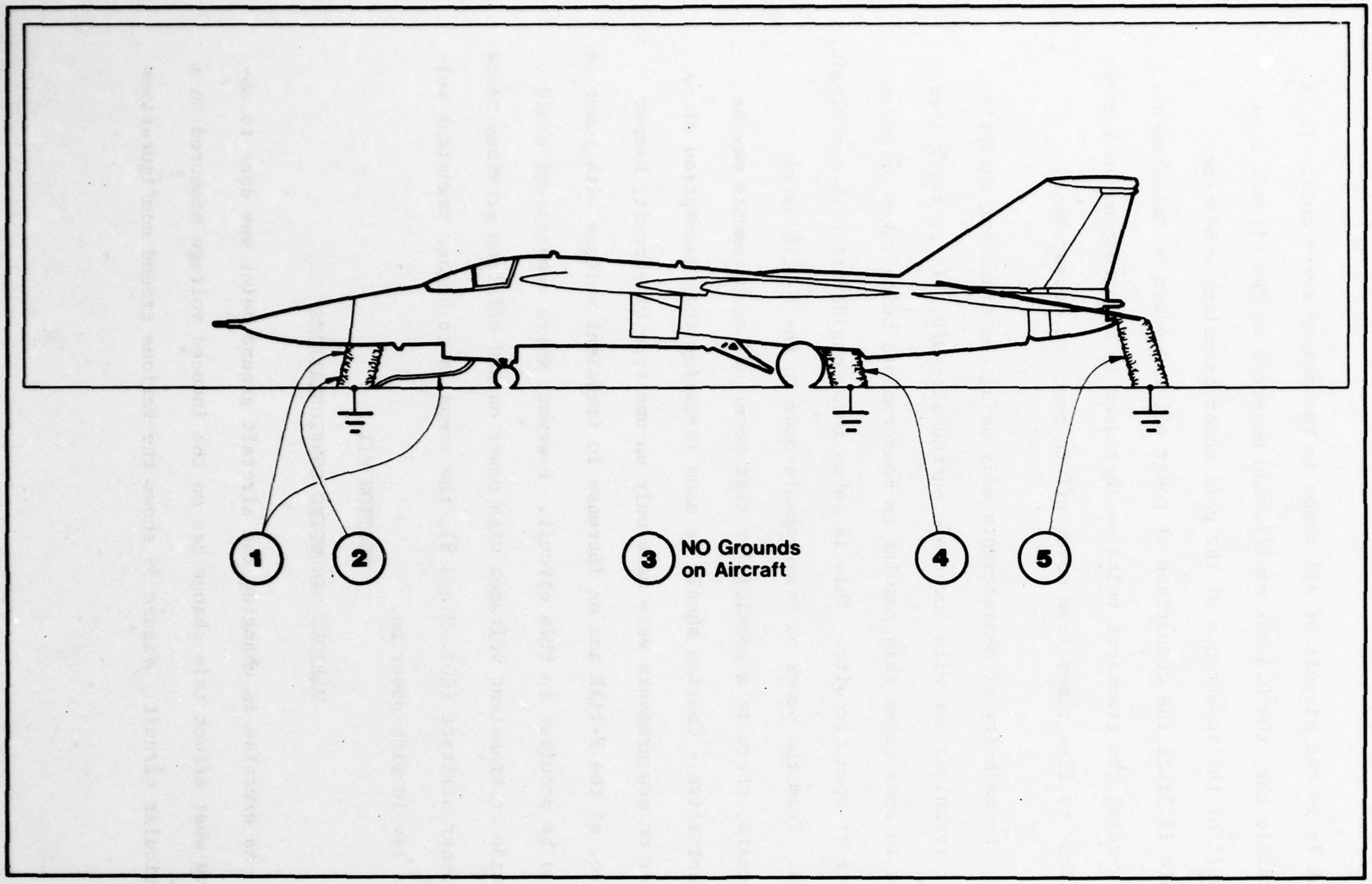


FIGURE 39

F111-E AIRCRAFT WITH VARIOUS GROUNDING CONFIGURATIONS

used. Table VI lists the various grounding configurations used and the induced voltage levels measured on circuit #10, Roll Damper Servo, Branch B, measured at the servo. From the magnitude of the voltages measured, no large variation in voltage occurred when the grounding was changed. This means that no significant currents are flowing through these ground paths. If there was current flow, the change in current path would affect the induced voltage level. This is not occurring. Also, the applied current impulse was monitored and found not to be affected by the ground variations. This fortified the supposition that there was no current flowing to ground through the paths described in Table VI.

SECTION VIII

REFLECTIONS ON THE CIRCUITS TESTED IN THE F-111 AIRCRAFT

To gain additional information on the electrical characteristics of the circuits tested in the F-111E aircraft, an investigation was made, analytically treating a few of the circuits as transmission lines and observing if reflections are propagated on the circuits.

To accomplish this investigation three of the circuits listed in Table II were subjected to a voltage impulse. The circuit diagram in Figure 40 shows the test set-up used. A pulse generator was used to inject a pulse on various conductors of the Damper Servo circuits at the test receptacle of the yaw computer and roll computer. Figure 41 shows the type of pulse injected onto the circuits.

TABLE VI

INDUCED VOLTAGE ON CIRCUIT #10 WITH AIRCRAFT GROUNDED AT VARIOUS POINTS

Grounding Configurations	Induced Voltage Volts		Induced Voltage @ 200 KA Volts		% Deviation from Average Voltage @ 200 KA	
	Positive	Negative	Positive	Negative	Positive 18.3 V avg	Negative 18.8 V avg
1. Aircraft grounded at access door 1201 with aluminum foil and (via the static ground line) at a point within the nose gear bay	.208	.216	19.0	19.8	3.8%	5.3%
2. Aircraft grounded at access door 1201 with aluminum foil	.230	.223	21.1	20.5	15.3%	9.0%
3. No grounds on aircraft	.190	.189	17.4	17.3	4.9%	8.0%
4. Aircraft grounded at left main gear well with aluminum foil to static ground point 30" of foil used	.195	.200	17.9	18.3	2.3%	2.7%
5. Aircraft grounded to extreme outer edge of left horizontal stabilizer with aluminum foil to nearby static ground	.178	.195	16.3	17.9	10.9%	4.8%
				Avg.	7.4%	6.0%

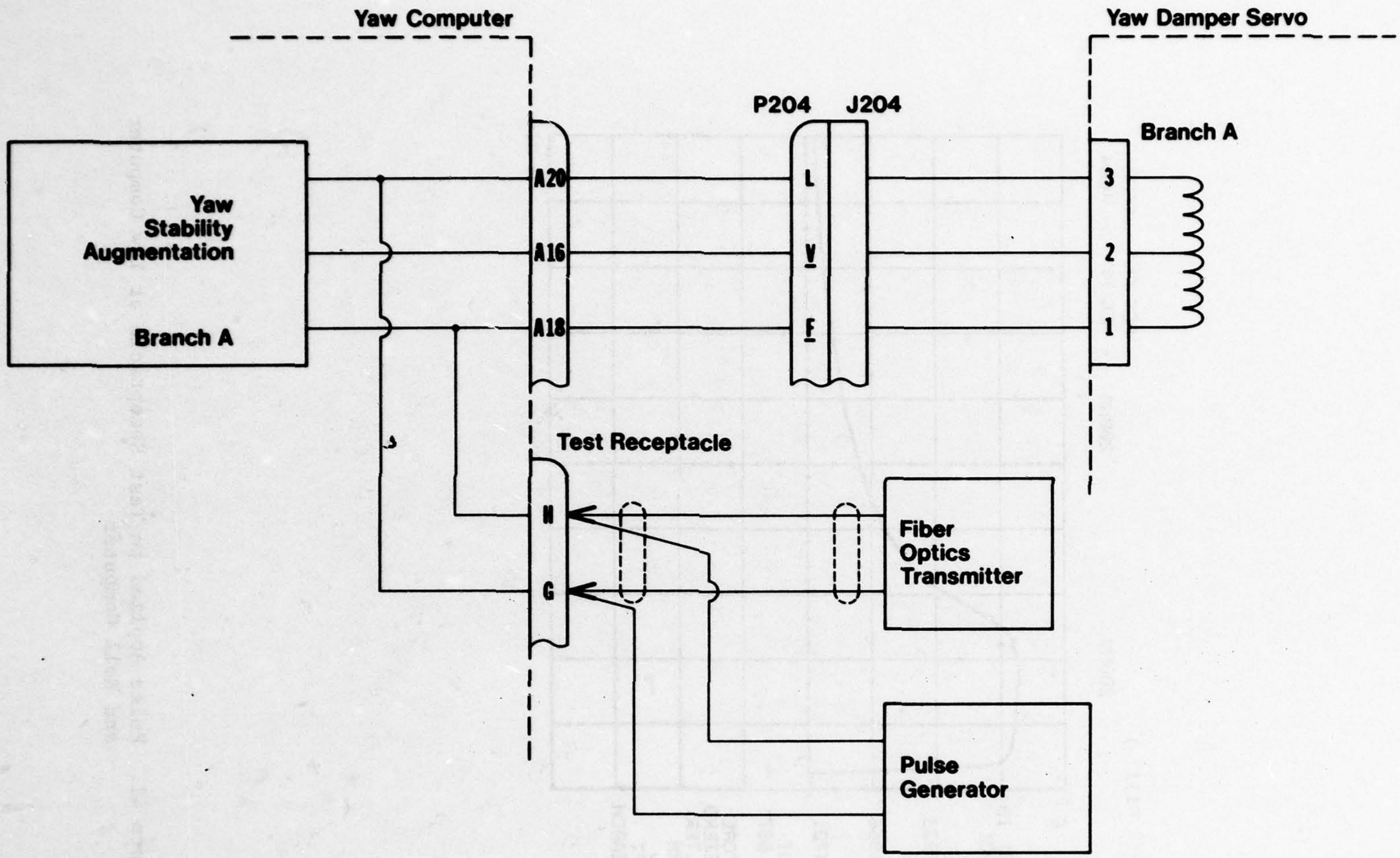


FIGURE 40

SET-UP FOR CIRCUIT REFLECTIONS INVESTIGATION

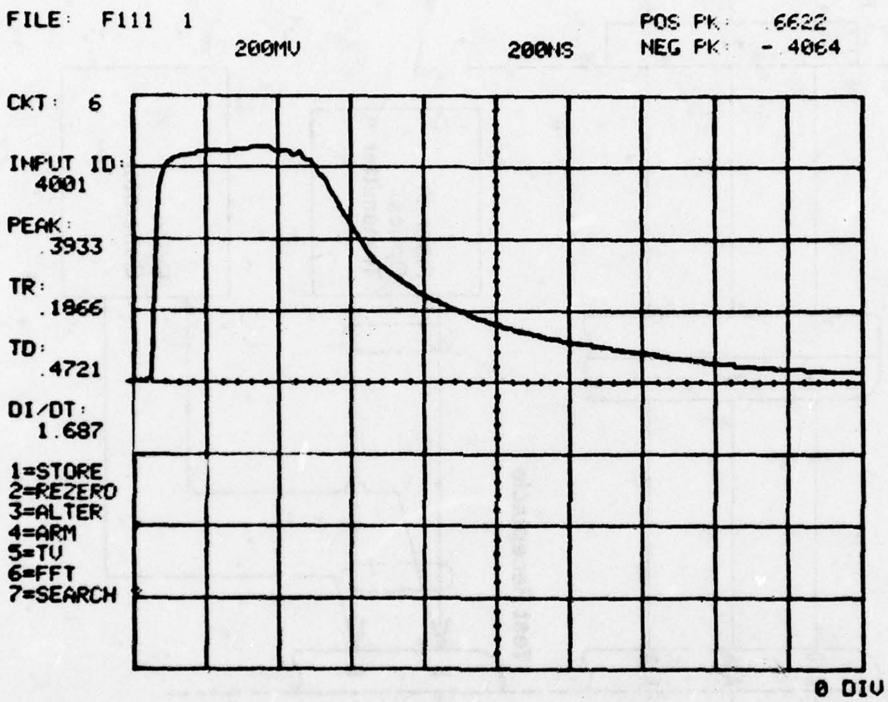
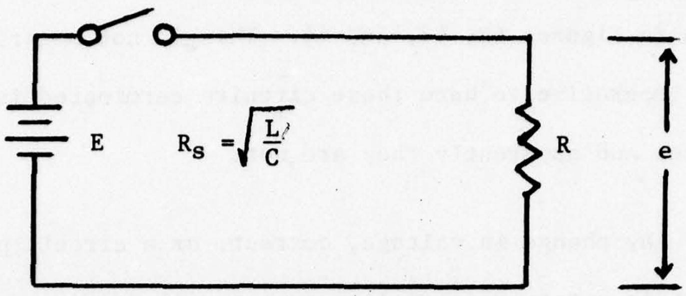


Figure 41. Pulse Applied to Test Receptacle at Yaw Computer and Roll Computer

The circuits tested can be represented by the following schematic:



where closing the switch initiates a wave of voltage e and current i:

$$i = \frac{E}{R_s} \qquad e = E$$

R = surge impedance and is equal to $\sqrt{\frac{L}{C}}$

L = inductance and C = capacitance of the circuit

From transmission line theory the ideal situation would be to have $R = R_s$, or matched impedances. A transmission line terminated in such a way would result in no reflected wave.

A transmission line with no reflected wave would transmit a given amount of energy more efficiently than one in which a reflected wave exists, since in the first instance the direct wave would supply the energy loss for transmission from sending to receiving end and the energy delivered to the load, whereas, in the second instance, additional energy would be necessary to supply the losses of a reflected wave. How this theory affects the investigation of reflections on the F-111 circuits is explained below.

To begin with, reflections were observed on all three circuits

that were subjected to the voltage pulse. These reflections can be seen in Figures 42, 43, and 44. This is not surprising since it is not imperative to have these circuits terminated in matching impedances and apparently they are not.

Any change in voltage, current, or a circuit parameter at any point in a transmission line system will initiate a traveling wave and a sequence of transients caused by reflections at a boundary or boundaries.

When the Yaw Servo circuit was pulsed (G-H on the Yaw computer test receptacle) the reflected wave was more than equal to the applied pulse. From measurements made on this circuit the following parameters were found:

$$L = 1.2 \text{ microhenries}$$

$$C \leqq 3 \times 10^{-9} \text{ farad}$$

$$R = 100 \text{ ohms}$$

The limit of the bridge used to measure capacitance was 3 nanofarads. For this explanation it will be assumed that the capacitance is approximately zero (i.e., less than 10^{-12} farad).

If the surge impedance, R_s, is equal to $\sqrt{\frac{L}{C}}$ then:

$$\sqrt{\frac{L}{C}} = \sqrt{\frac{1.2 \times 10^{-6}}{0}} = R_s \gg R$$

From transmission line theory:

$$e' = e\left[\frac{R - R_s}{R + R_s}\right]$$

where e = applied pulse e' = reflected pulse

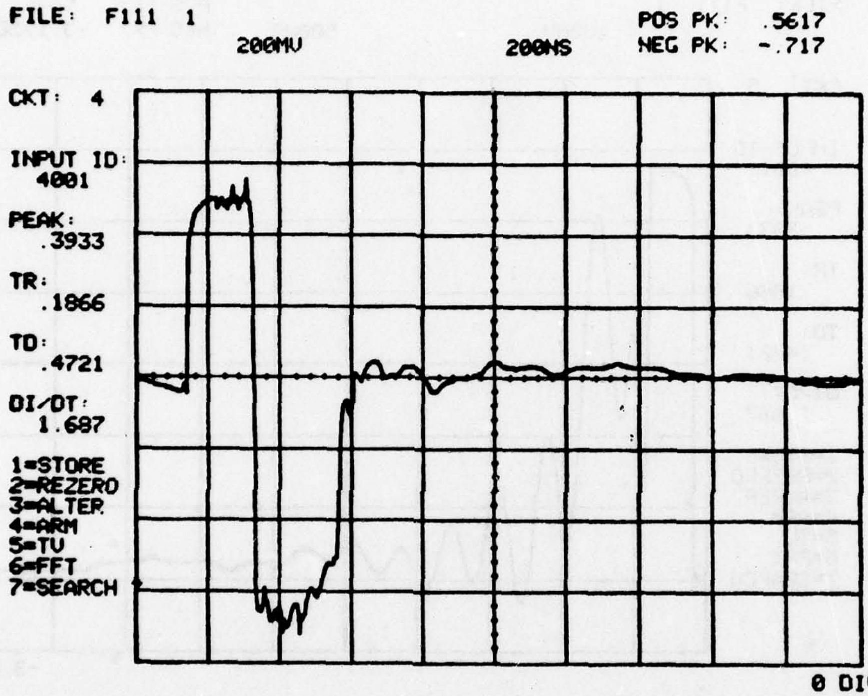


Figure 42. Reflected Voltage Wave on Circuit #4 Yaw Computer, Test Receptacle, Pins G-H, Branch A

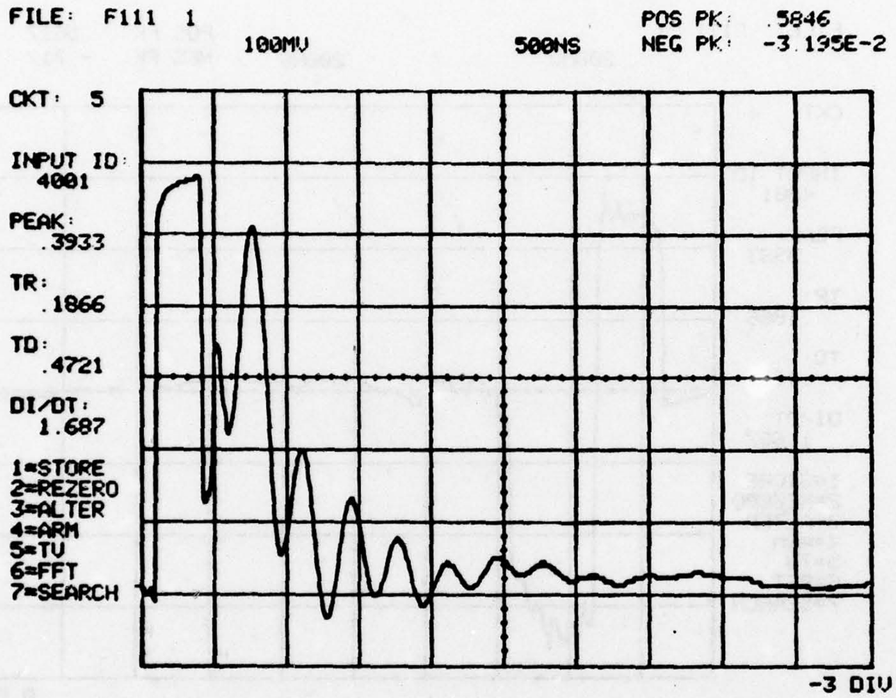


Figure 43. Reflected Voltage Wave on Circuit #5 Yaw Computer, Test Receptacle, Pins J-E, Branch B

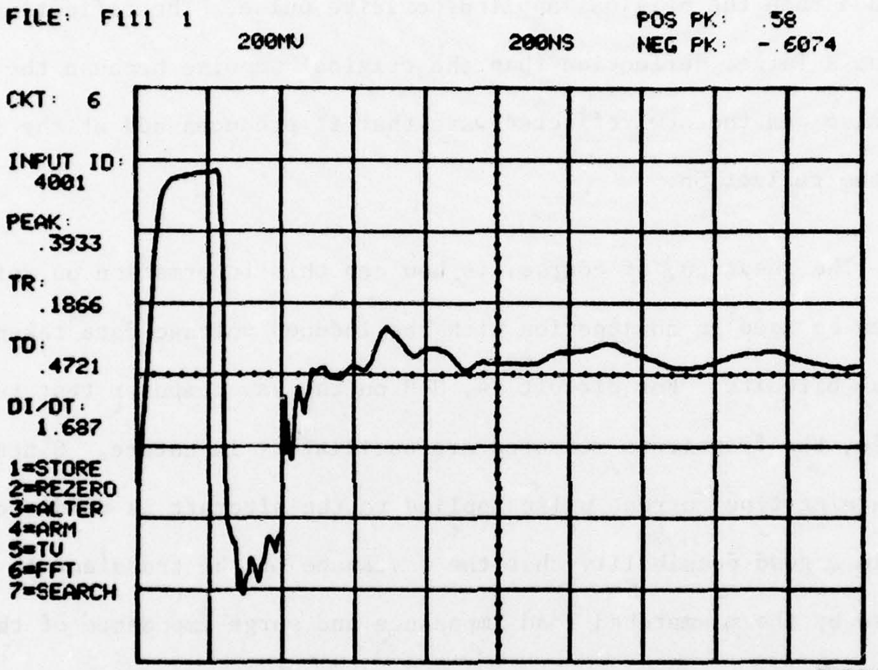


Figure 44. Reflected Voltage Wave on Circuit #6 Roll Computer, Test Receptacle, Pins J-E, Bsanch B

therefore if $R_s \gg R$, then $e' \simeq -e$.

From Figure 42 and the parameter measurements L, C and R, this seems to be the case.

It is noted that the negative reflected wave is larger in magnitude than the original applied positive pulse. The reflection produces a larger deflection than the original impulse because the reflected impulse and the new reflected wave that it produces add at the instant of the reflection.

The question, of course, is how can this information on reflected waves be used in conjunction with the induced voltage data taken on these circuits. For circuit #4, G-H on the yaw computer test receptacle, the transients measured are oscillatory in nature. Since the lightning type current pulse applied to the aircraft is unidirectional, it is a good possibility that the waveshape of the transient is influenced by the mismatched load impedance and surge impedance of the circuit and, therefore, an oscillatory transient results. For circuit #5, J-E on the yaw computer, the reflected waveshape, Figure 43, is a damped positive oscillation. The reason there is a negative reflection on the other circuits and a positive reflection on circuit #5 is that there is a difference in impedance mismatch between circuit #5 and circuits #4 and #6.

SECTION IX

STATISTICAL AVERAGING OF TRANSIENT ANALYSIS RESULTS

One of the primary objectives of the lightning research program done on the F-111E aircraft was to improve the accuracy of the tran-

sient voltage data taken by increasing the number of measurements made on a particular circuit.

The magnitude of the transient observed on a circuit is influenced by several factors. Current distribution, geometry of the aircraft structure, circuit shielding, and type of circuit are some of these factors. The induced transient is created by current flow down the aircraft and it is the magnitude of this impulse current that is a major factor in determining the magnitude of the transient.

The applied current pulse magnitude is directly proportional to the charge voltage on the capacitors of the pulse generator. The DC charging voltage is obtained through a rectifier network whose source is 60 Hz 115 VAC. If the magnitude of the 60 Hz voltage should vary, the DC voltage will vary a proportional amount. This would mean that the charge voltage on the capacitors would vary, thus varying the magnitude of the current impulse. This possible change is known by the personnel operating the generator and, in fact, the charging voltage, both from the rectifier system and the actual charge on the capacitors, is monitored at all times. However, a variation of less than a hundered amperes can affect the induced transient magnitude.

Therefore, to increase the accuracy of the transient measurements, a minimum of five consecutive measurements was made on each of the circuits tested in the F-111E.

The magnitude of the impulse current applied to the F-111E aircraft varied from 0.49 kiloamperes to 5.5 kiloamperes. Most of the transient measurements were made at a current level of 2.49 kiloamperes. Only on circuits #4 and #12 were the current magnitudes varied to some extent to obtain information on the linearity of transient voltage with respect to current magnitude.

SECTION X

EXTRAPOLATION OF TRANSIENT LEVELS

One of the controversial aspects of lightning transient investigations is the extrapolation of transient magnitudes up to full threat level. In other words, this would be the induced transient produced by a 200 kiloampere current wave with a risetime of 2 microseconds and a fall time to half value of 50 microseconds. This magnitude and waveshape have been recognized as the standard full threat level (Ref. 9) and, as such, are used as a guideline for vulnerability assessment of aircraft electrical and electronic systems.

Because of the possible damage to the electronic systems of an operational aircraft by the 200 kiloampere current and also because of the difficulty in obtaining a current wave of such magnitude and waveshape, most transient investigations are done using a current level lower than 200 kiloamperes. It has been possible during recent transient investigations on aircraft to observe the degree of linearity of different circuits when the applied current is varied in magnitude.

Any discussion on linearity should also include a discussion of the parameters that can affect linearity. Two of these parameters are magnitude and rate-of-rise of the applied current wave. The greater the rate-of-rise of the current wave, the greater the level of transient voltage induced on the circuits (Ref. 4). Other factors such as type of wire (coaxial, twisted pair, shielded, unshielded) and position in the aircraft affect the magnitude of the transient voltage.

As explained earlier in this report, it is possible for the charging voltage to the lightning current impulse generator to vary sufficiently to change the peak magnitude of the applied current wave. Since the magnitude of the applied wave directly affects the magnitude of the induced transient on a circuit, more valid information can be gained by taking a number of measurements on a selected circuit.

Figure 45 is a linearity study done on the tail light circuit, circuit #12. The bar lines present on the graph denote a data spread at each applied current level. If one measurement were made at each applied current level, there is a possibility that this data, when presented in graph form, would appear distorted. For instance, from Figure 45, if only the high data points were recorded at the 4.0 kA and 4.5 kA levels and only the low data point were recorded for the 5.5 kA level, the resultant line drawn through the points to express linearity would tend to roll off

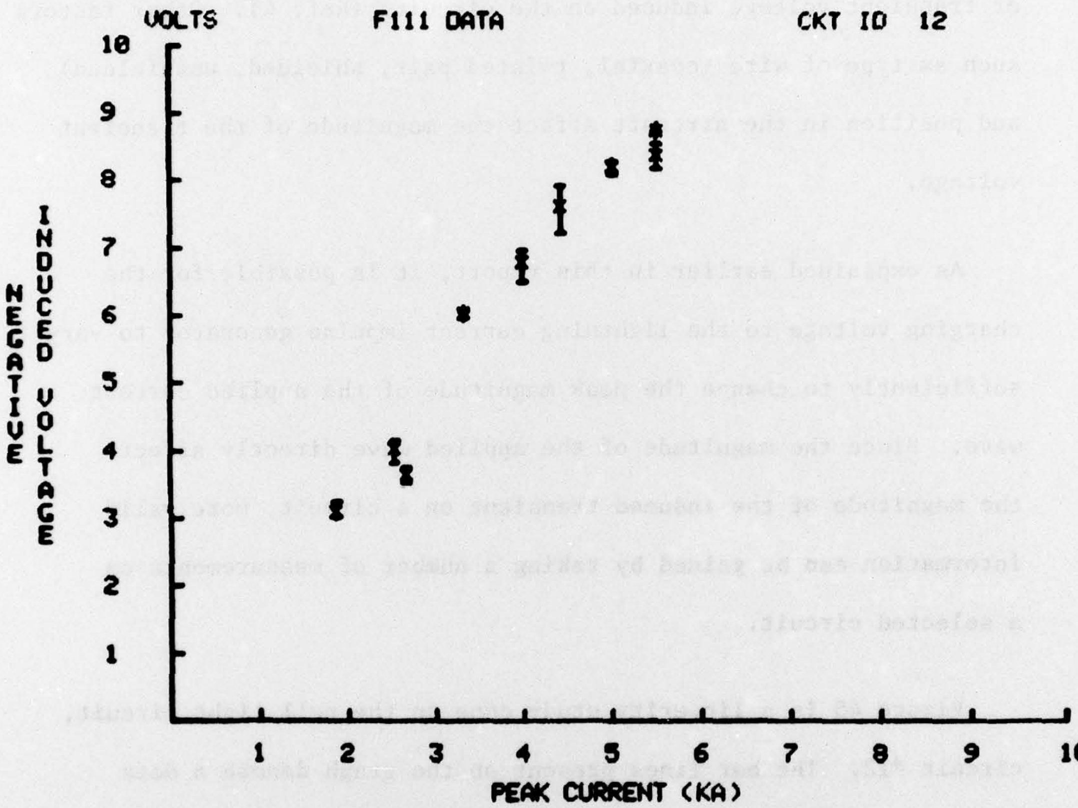


Figure 45. Tail Light Circuit, Induced Voltage Versus Applied Current Magnitude.

after the 5.0 kA level. This would call into question the validity of the linearity concept. With the spread of data taken, it is possible to uphold linearity above the 4.0 kA level.

Another case would arise if only high data points were recorded at the 1.8 kA and 2.5 kA levels. A line drawn through these points would not go through the zero reference and therefore would cast additional doubt on the validity of the data.

Figures 46 and 47 show induced voltages at different applied current levels measured on circuit #4, the Yaw Damper Servo at the computer. The results on this circuit are in sharp contrast to the linear increase in induced voltage observed on the tail light circuit. There seems to be no relation of increased applied current to the measured voltage. If any pattern can be discerned, it is that the induced voltage seems to "clamp" at a certain level, approximately 0.2 volts, as the applied current increases. The validity of this data would be questionable if the same results were not found on similar circuits on the YF-16 (Ref. 4). It is possible that the electronics associated with the servo output amplifier of these servo circuits limits the voltage across the measured circuit. Figure 15 is a schematic of the Roll Damper Servo which is identical to the Yaw Damper Servo. The diodes in this circuit may break down electrically to provide the voltage limiting.

Again, if only one voltage measurement were made at the different

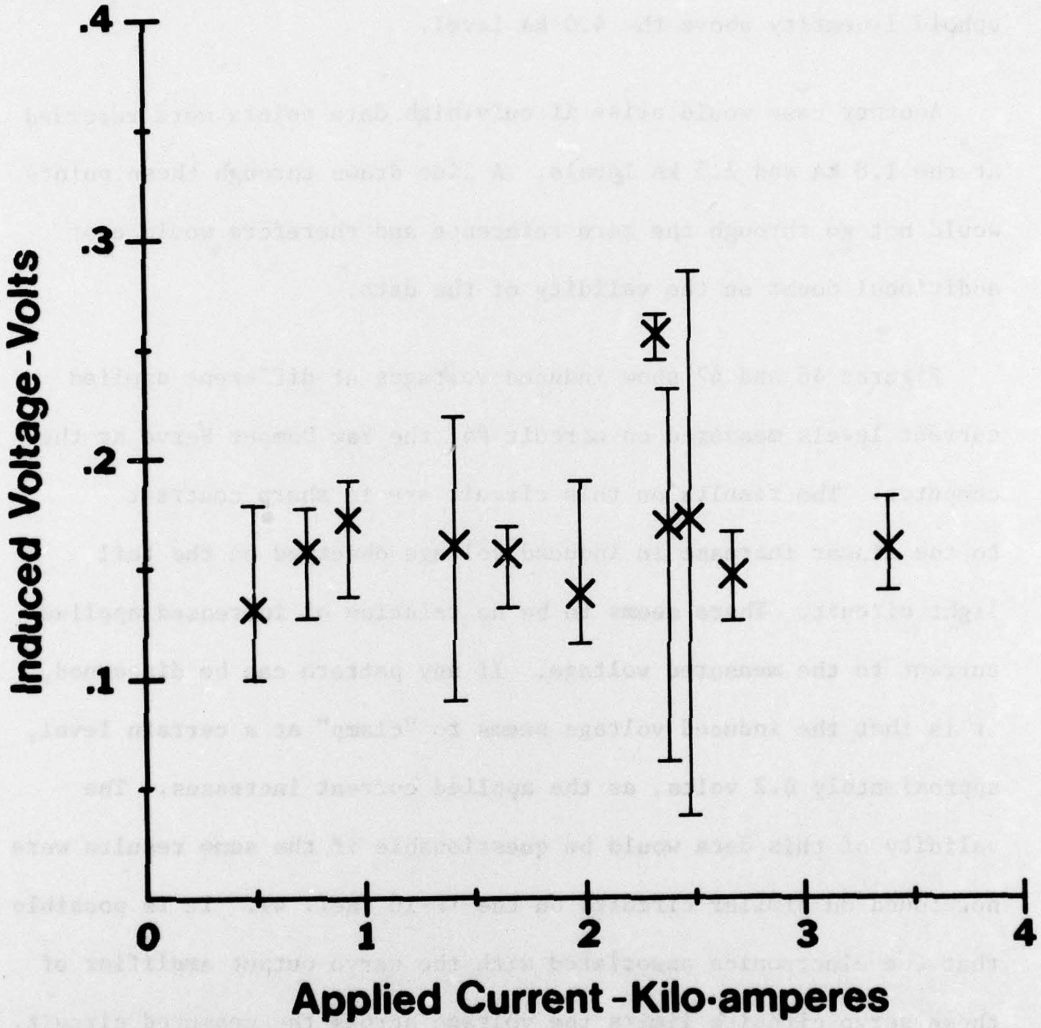


FIGURE 46

YAW DAMPER SERVO (CIRCUIT NO. 4)
POSITIVE INDUCED VOLTAGE VERSUS
APPLIED CURRENT MAGNITUDE

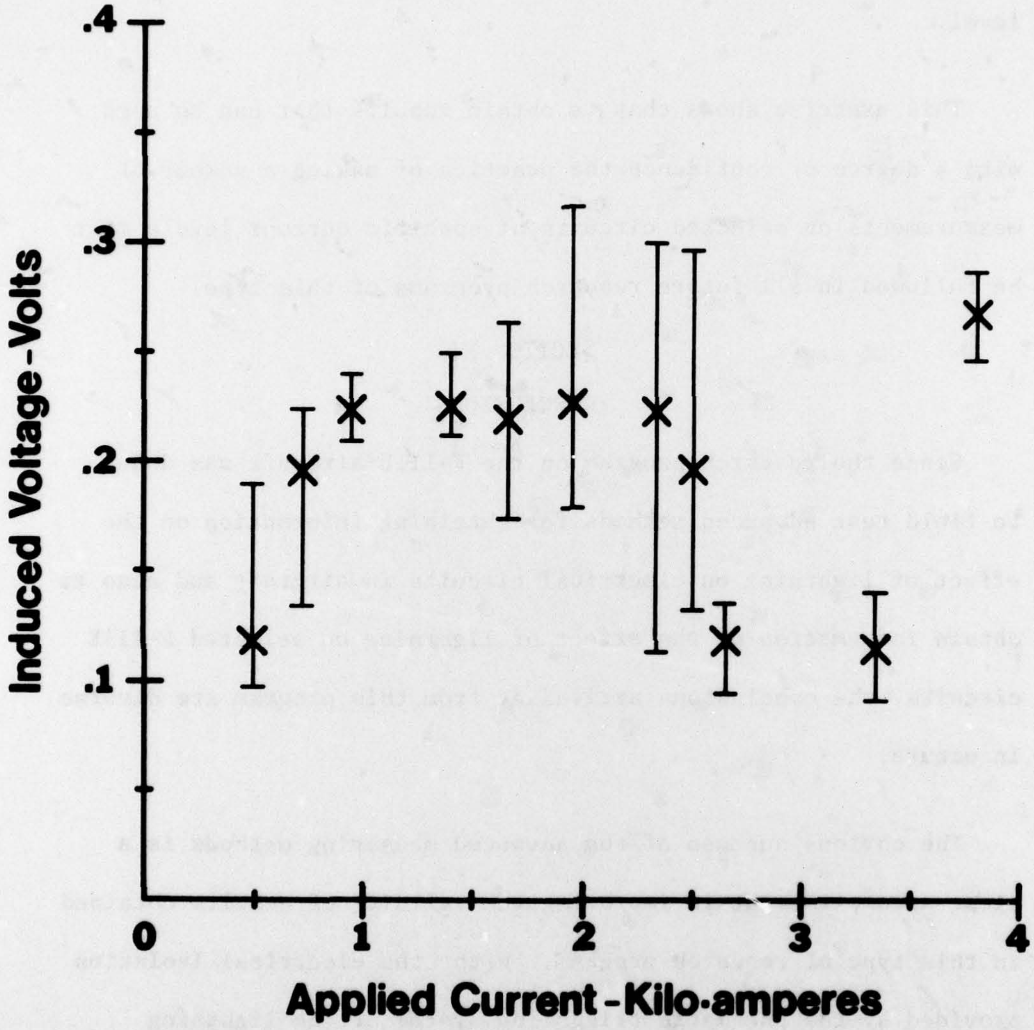


FIGURE 47

YAW DAMPER SERVO (CIRCUIT NO. 4)
NEGATIVE INDUCED VOLTAGE VERSUS
APPLIED CURRENT MAGNITUDE

applied current levels, the response of the Yaw Servo circuit could be misinterpreted. Figures 46 and 47 show the spread of data for each level.

This exercise shows that to obtain results that can be used with a degree of confidence the practice of making a number of measurements on selected circuits at specific current levels must be followed in all future research programs of this type.

SECTION XI

CONCLUSIONS

Since the research program on the F-111E aircraft was done to field test advanced methods for obtaining information on the effect of lightning on electrical circuits in aircraft and also to obtain information on the effect of lightning on selected F-111E circuits, the conclusions arrived at from this program are diverse in nature.

The obvious success of the advanced measuring methods is a clear accomplishment in improving the validity of results obtained in this type of research program. With the electrical isolation provided by the pneumatic triggering system of the lightning current producing capacitor bank and the transient measuring system, including the break-out boxes, fiber optics and digitized data recording system, the credibility of the lightning transient test technique has been increased.

From the induced transients measured on specific F-111E cir-

cuits, the higher transient values measured with power on the aircraft indicate the need to take all subsequent measurements on circuits with power on to obtain more representative values of transients due to lightning.

The pitot heater circuit has a unique lightning problem that seems to have a solution in the use of a transient suppressor device mounted at the radome disconnect.

For the servo circuits the pulse reflection measurements explain the oscillatory nature of the induced transient waveshapes measured on those circuits. Mismatched load impedances and surge impedances may account for the oscillatory transients measured on other circuits. Impedance measurements should be made on all circuits in future research programs to verify this.

Evidence for the credibility of the linear extrapolation concept was improved by increasing the number of measurements made at each current level to obtain a mean transient value.

Some of the circuits tested were chosen because similar circuits have experienced problems when actual aircraft were struck by lightning. The Altitude-Vertical Speed Amplifier is part of such a circuit. The AVSA serves as a power supply and amplifier for the Altitude-Vertical Velocity Indicator. From Table II the voltages measured on the AVSA are relatively higher than those on the damper servo circuits. There are higher voltages measured on the tail light

and pitot heater circuits. But the tail light circuit uses the skin as circuit return and the pitot heater is especially vulnerable due to its location on the aircraft. The voltages measured on the AVSA support the information that this circuit is more susceptible to lightning induced transients than other circuits of its type and function.

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